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THE WORK OF BENJAMIN FRANKLIN ON THUNDERSTORMS AND THE DEVELOPMENT OF THE LIGHTNING ROD

BY

B. F. J. SCHONLAND[1]

SUMMARY

An account is given of the experiments and hypotheses which led Franklin to propose (*a*) the "Philadelphia Experiment" (10th May, 1752) on the identity of laboratory and thunderstorm electrification and (*b*) the lightning rod as a protective device. These and Franklin's other experiments and ideas on lightning and thunderstorms are surveyed in the light of modern knowledge.

His conception that one function of the lightning rod was to neutralise all or part of the charge on the cloud-base by point-discharge is shown to be correct in the exceptional case of an extremely high rod, which was his original view. Rods of moderate height are not able to do this but perform the second function suggested by him, drawing the discharge to them and leading it safely to ground.

I. INTRODUCTION

1. The tenth of May of this year 1952 marks the 200th anniversary of the successful conclusion of a series of investigations of genius, which in their day rightly evoked the admiration of the civilised world. After two hundred years the greatest of the "Philadelphia Experiments" stands out as an achievement remarkable both for the reasoning by which it was reached and for the fact that it was the product of the mind of a self-taught man who was far removed from contacts with men of similar intelligence and interests, from sources of information and laboratory equipment and from the great scientific academies which for over a century had provided the driving-force behind the advances of knowledge in the Old World.

The honours which were showered on Franklin after the success of this experiment and after the introduction of the lightning rod have done some injury to his reputation as a scientific investigator and thinker. The public, then as now, loves an "inventor" and has, until

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[1] The Bernard Price Institute of Geophysical Research, University of the Witwatersrand, Johannesburg, South Africa.

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recently, had little understanding of the work of an experimental scientist. Franklin's investigations have been unjustly labelled those of an "amateur and a dabbler" (**1**),[2] an opinion which could be held only by someone who had not read carefully his collected reports on his work. These show that he was a natural philosopher of very great stature and an amateur, like Cavendish, in the best sense of the word.

A valuable general survey of Franklin's research work and of the state of electrical knowledge before 1746 has been given by I. Bernard Cohen (**2**) as an introduction to his recent edition of Franklin's "Experiments and Observations on Electricity." The present paper is devoted to an examination and appreciation of Franklin's work on thunderstorms and on the lightning rod.

Franklin's minute-book, the journal in which he noted daily his ideas and the results of his experiments, has been lost. The only material from which to follow his work and that of his friends and assistants in the remarkable ten years from 1746 to 1756 is contained in various editions, prepared by Franklin himself, of his letters to his friend Peter Collinson of London (who communicated them to the Royal Society) and to other correspondents. These can be described as lying halfway between progress-reports and scientific papers. They are not easy to read; the many new conceptions of electrical phenomena which occupied the mind of the author jostle each other for space and it is sometimes hard to follow their development. At times one is at a loss to understand how he came to suggest some important new idea, until careful examination of a previous letter shows one sentence which provides the link in the chain of his argument, and proves that he was not working on a "hunch" but on a closely-reasoned placing of experiment upon experiment and argument upon argument.

2. Franklin and his friends, Thomas Hopkinson, Ebenezer Kinnersley and Philip Syng, of the "Library Company of Philadelphia" began their investigations in 1746. It was the period of drawing-room demonstrations of frictional electricity. It was also the year of the discovery of the condenser or Leyden jar. They were from the beginning interested in the meaning of these amusing manifestations of "the electric fire." In 1747 Franklin wrote "For my own part, I never was before engaged in any study which so totally engrossed my attention and my time as this lately has done." (**3**). In that same year he communicated to Collinson his conception of electricity as "an element diffused among, and attracted by other matter" (**4**). On this view all bodies have a "common stock" of electricity which can be added to or subtracted from by suitable means, causing them to become positively or negatively charged. The new one-fluid conception of electricity gave Franklin an insight into many complex electric phenomena, including the condensing property of the Leyden jar, and was of course an anticipation of modern ideas on the electrical structure of matter, in which electrons, detached from atoms, comprise the "subtile fluid."

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[2] The boldface numbers in parentheses refer to the references appended to this paper.

That the electron "fluid" is actually in excess under conditions which Franklin called in defect was of no real importance for his experiments or for the deductions he made from them.

3. Throughout the letters to Collinson from 1747 onwards, three distinct threads of enquiry were closely woven. The first, with which this paper is not directly concerned, was the application of the one-fluid theory to a variety of experimental observations, the second the working towards a long-sought direct proof of the identity of thunderstorm and laboratory-made electricity, and the third was a strong desire to find practical use for some portion of the new knowledge, a desire which was to culminate in the extraordinary proposal of the lightning rod. In 1748, only two years after he had begun, he wrote that they were "chagrined a little that we have been hitherto unable to produce nothing in this way of use to mankind" (5). In 1753, however, he was able to write in *Poor Richard's Almanac*, "It has pleased God in His goodness to mankind at length to discover to them the means of securing their habitations and other buildings from mischief by thunder and lightning." (6).

II. FRANKLIN'S THUNDERCLOUD THEORIES AND EXPERIMENTS

4. Franklin's study of thunderstorm electricity sprang from the investigations of Hopkinson and himself on point-discharge. In his first scientific communication of May 1747 he wrote to Collinson: "If you present the point (of a long needle connected to earth) in the dark, you will see sometimes at foot distance or more, a light gather upon it like that of a fire-fly or glow-worm; the less sharp the point the nearer you must bring it to observe the light; and at whatever distance you see the light, you may draw off the electric fire." (7).

By 1750 he has a clear idea of the rôle of high surface density in causing point-discharge *from* a charged body which he explains by saying that an insulated conductor "having its own natural quantity of the electrical fluid" is, when charged, surrounded by an "electrical atmosphere" which resides on or near the surface. Excess or positive charge is not only attracted by the body itself so that it normally remains with it, but also exercises repulsion on its component parts, which reduces this attraction. At the extremity of a pointed conductor, where what we would now call the "surface-density" is greatest, "the quantity is largest and the surface to attract and keep it back the least . . . so that the atmosphere continues flowing off like a stream till no more is remaining." From this he formulates a "law of electricity" that the sharper the point the more effective it is in discharging the conductor (8).

He explains further that the electricity is carried by the non-conducting air in point-discharge because it has "water and other non-electric (conducting) matters mixed with it; and these attract and receive what is so discharged" (9). This general statement would cover what we would now call the positive ions in the air and was a hypothesis which could usefully lead to further experimental discovery.

Franklin does not seem to have had at this stage a clear conception of the action of an earthed point in "*drawing-off*" electricity from a charged body, but he proceeded to perform a very significant experiment with an insulated point. He constructed a large and imposing insulated conductor of pasteboard covered with Dutch metal, ten feet in height and one foot in diameter, which he hung from the ceiling by silk cords and charged with his frictional electric machine. This conductor gave a two-inch spark to earth when a blunt rod was brought near it, but could be discharged silently and completely by a person holding an earthed bodkin a foot away, even if it was continuously connected to the machine. He then made a most important observation which is the key to all his later work. He insulated the discharging point and remarked "And if the person holding the point stands upon wax, he will be electrified by receiving the fire at that distance (one foot)." (10).

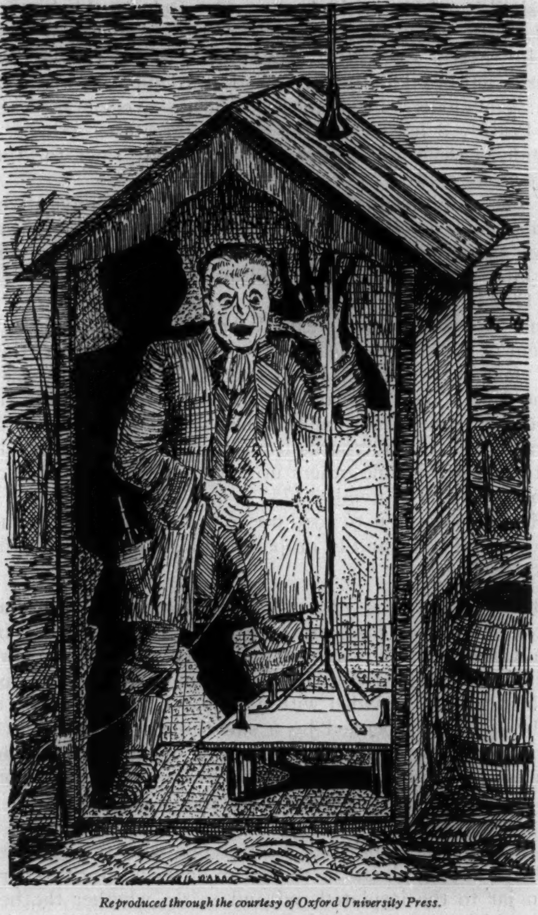
This single sentence is all that is on record of a discovery which led immediately to the "Philadelphia Experiment" (10a) on the identity of laboratory and thunderstorm electricity.

Franklin was not able to offer any explanation of the result itself. Like the discharging action of an earthed point it would have required the conception of the ionisation of the air and of the creation of a second type of carrier, the negative ion, with a *defect* of the electric fluid, and this he did not envisage. Indeed, he commented "Nor is it of much importance to us, to know the manner in which nature executes her laws; it is enough to know the laws themselves." He considered that these were pleasant matters of speculation and hoped that his inadequate ideas on this difficult subject might lead to a satisfactory solution "in the mind of an ingenious reader" (11).

The fact was that he saw at once from these experiments that "this power of points may possibly be of some use to mankind, though we shall never be able to explain it" (11). In the next few paragraphs of the same communication to Collinson and the Royal Society he outlined his two great proposals for the performance of the Philadelphia Experiment and for the installation of lightning rods. The second of these will be discussed later (§ 9); the first he put forward as follows (12):

> To determine whether clouds that contain lightning are electrified or not, I would prepare an experiment to be tried when it may be done conveniently. On the top of some high tower or steeple, place a kind of sentry-box, big enough to contain a man, and an electrical stand. From the middle of the stand let an iron rod rise and pass bending out of the door and then upright 20 or 30 feet, pointed very sharp at the end. If the electrical stand be kept clean and dry, a man standing on it when such clouds are passing low might be electrified and afford sparks, the rod drawing fire to him from a cloud. If any danger to the man should

be apprehended (though I think there could be none) let him stand on the floor of his box and now and then bring near to the rod, the loop of a wire that has one end fastened to the leads (earth), he holding it by a wax handle; so the sparks, if the rod is electrified, will strike from the rod to the wire, and not affect him.



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The first test of the "Philadelphia Experiment" on May 10, 1752, drawn by Dr. Mary Schonland.

5. This was the proposal for *the* "Philadelphia Experiment." The story of its successful executon is well-known (13). At Marly near

Paris, a pointed iron rod 40 feet high, ingeniously insulated and protected against rain leakage, was erected by D'Alibard and on May 10, 1752 was sufficiently affected by a nearby thundercloud to give a continuous series of sparks to an earthed wire held near it. A week later a similar rod 99 feet high, set up by Delor on his house in Paris, showed similar effects, giving sparks nearly an inch long. Successful results by several English investigators were reported a few months afterwards and Franklin, before he had heard about it, was acclaimed in Europe as a modern Prometheus. The discovery was described by Joseph Priestly a few years later as "the greatest, perhaps, that has been made in the whole compass of philosophy since the time of Sir Isaac Newton" (**13d**).

The successful results obtained from these comparatively short conductors made it clear to Franklin that in proposing the use of a steeple or tower he had underestimated the magnitude of the effect. Even a kite, with a string insulated at its lower end, which he used in June 1752 in default of a steeple, had proved unnecessary. In fact, his friend Kinnersley nine years later successfully used "your old experiment of the kite" to measure the electricity of the air (the electric field) in clear dry weather (**14**). Under such conditions the field, and hence the effect sought for, would be several hundred, if not a thousand, times weaker than the strong field below a thundercloud. That the latter would give rise to sparks from a rod of moderate height was a pleasant surprise. While others in Europe were marvelling about it, Franklin as early as September 1752, a few weeks after he had heard of the result, was turning it to good use to measure the sign of the charge on thundercloud bases and to propose the installation of lightning rods as protective devices.

6. With the first of these objects in view he erected an insulated iron rod on the chimney of his house in Philadelphia. The lead from this rod terminated "opposite my chamber-door" and was separated by about six inches from a wire leading to an iron water-pump. Each end of this gap was provided with a little bell "and between the bells a little brass ball, suspended by a silk thread, to play between and strike the bells when clouds passed with electricity in them" (**15**). These "electric chimes" were to give warning of electrification of the rod. To test the sign of the charge on the rod he suggested two methods: the first was to collect some of the charge in a Leyden jar and to compare it by means of a cork ball electroscope with the positive charge obtained by rubbing glass; the second to apply a positive charge from a Leyden jar to the insulated rod and to see whether the bells rang faster, in which case the cloud charge would be positive, or stopped ringing for a time, when it would be negative (**16**).

As will be explained in § 7, he expected the clouds to be positively charged, but he found, in April 1753 (**17**), that in most cases they were negative. This conclusion was supported by further trials by Kinnersley, by Canton in England and by Beccaria in Italy (**18**). Both Franklin and Kinnersley noticed that towards the end of the passage of a storm overhead the sign of the cloud-charge altered to positive. All these results are in agreement with many observations made within the last thirty years. Apart from a small positive pocket, which is not always evident, the bases of active clouds all over the world have been found to be negatively charged (**41**). Franklin's observation that the rear of a thundercloud, from which little, if any, lightning comes, is positively charged, has been repeated by the author and others. It is presumably due to the descent during the disintegrating phase of the storm of the positive charge which in the active phase lies high above the negatively-charged base and could not have been detected by Franklin's method of study.

These very beautiful experiments on the sign of thundercloud charges were the last Franklin was able to make. The rest of his life was spent in the service of his country.

7. As early as 1747, at least six years before he was able to establish the fact of thunderstorm electrification and to test its sign, Franklin was considering in his mind how clouds become electrified, and this problem evidently occupied him a great deal both before and after the experiment described in the last section. That it was the one question to which he failed to provide a successful answer is not surprising, since there is at the present day no final agreed answer to it.

He began with a mistaken assumption; he thought it self-evident that the luminosity or phosphorescence of sea-water when agitated at night was due to an electrical glow. This he explained as caused by the friction of minute conducting particles of salt with non-conducting water. He argued then that the process of evaporation of sea-water would provide uprising water-vapour, and the clouds formed by it, with a positive charge. Such clouds when they encountered mountain-chains or other non-electrified clouds formed over land, or came near prominent trees or buildings, would discharge their electricity to them (**19**).

In 1750 and 1751, "being occasionally on the sea-coast," he convinced himself that he had "embraced this opinion too hastily" because he had had "no opportunity of making experiments on the sea-water." For when he did experiment with agitated sea-water he found that its luminous appearance "must be owing to some other principle" (**20**) (which his friend Governor Bowdoin in 1753 correctly found to be the presence of floating animalculæ). He therefore made a number of trials of other possible methods of electrification.

His next surmise was that air might become negatively charged by *friction* against the conducting earth. But an experimental trial with a violent stream of air from his bellows did not succeed (**21**).

It is of interest that the "frictional" impact both of ice-particles upon one another and of waterdrops breaking up in an ascending stream of air are now known to be factors in the electrification of thunderstorms, though it is not considered that they are the main generating mechanism (**41**).

He then thought, after experimenting with the change of surface-density of conductors with surface area, that the electrification might arise from the *change of state* from water to water-vapour. "When a portion of water is in its common dense state, it can hold no more electric fluid than it has; if any be added it spreads on the surface. When the same quantity of water is rarified into vapour and forms a cloud, it is then capable of receiving and absorbing a much greater quantity . . . thus water . . . in the form of a cloud . . . will have less than its natural quantity" and "will be in a negative state" (**22**). It is easy to smile at this explanation, but in fact electrification during the *change of state* from water to ice in the upper regions of a thundercloud offers at present the most satisfactory explanation we have of the main mechanism of the thundercloud (**32**, **41**). If Franklin had known the temperature conditions in clouds he would no doubt have suggested it.

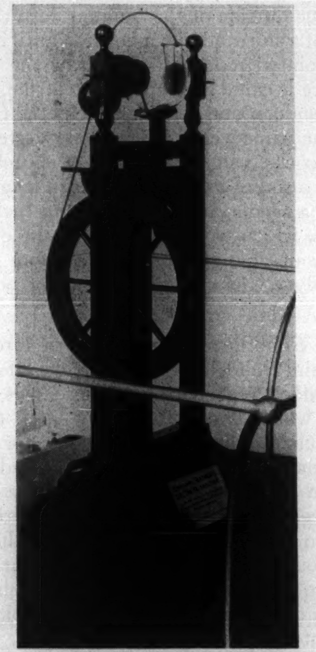
He was first and last an experimentalist and he goes on to say: "Perhaps some future experiments on vapourised water may set this matter in a clearer light." In 1762 he wrote of experiments he had made "to try if negative electricity might be produced by evaporation only" but he could find no such effect (**23**).

III. THE LIGHTNING ROD

8. When asked in 1755 how he "came first to think of proposing the experiment of drawing down the lightning, in order to ascertain its sameness with the electric fluid," Franklin gave his enquirer an extract from his minute-book for November 7th, 1749, in which he had listed the points of similarity between lightning and the electric fluid. The list ended with the words "The electric fluid is attracted by points. We do not know if this property is in lightning. But since they agree in all the particulars wherein we can already compare them, is it not probable they agree likewise in this? *Let the experiment be made.*" (**24**).

In the same year 1749 he noted "If two gun-barrels [the usual metal conductors charged by his electric machine] will strike at two inches distance, and make a loud snap, to what a great distance may 10,000 acres of electrified cloud strike and give its fire and how loud must be that crack?" (**25**). Similar remarks are scattered through his earlier letters to Collinson showing how, like earlier workers with electricity, he came to the conclusion that lightning was an electric spark on a grand scale and that its effects could without doubt be reproduced ("bottle may be added to bottle *ad infinitum*") by charging and discharging a sufficient number of condensers in parallel.

9. The first suggestion for the installation of lightning rods was made by Franklin in 1750, after performing experiments in 1749 which included the large insulated cylindrical conductor described in § 4. He found that on bringing up to it an earthed iron punch with a rounded end, the suspended conductor "will move towards the punch, being attracted while it is charged; but if, at the same instant, a point be presented as before, it retires again, for the point discharges it . . . the greater (the) quantity of electricity on the pasteboard tube, the farther it strikes and discharges its fire and the point likewise will draw it off at a still greater distance." (**26**). From this and a similar experiment with a large pair of scales, one of whose pans was insulated and charged, he drew the following deductions:



Franklin's electrical machine, somewhat altered by the addition of a comb to collect the charge.

(*a*) if thunderstorm and laboratory electricity are the same the experiment may be taken to represent conditions under a thundercloud, dimensions being appropriately scaled down;

(*b*) the attraction of the suspended conductor by a blunt rod before sparking takes place should be represented on the larger scale by the downward movement of a cloud towards a hill or high building, which would pull the cloud to within its "striking distance";

(*c*) since a needle near to or on the blunt punch discharges the conductor silently, the same thing could be made to happen to a thundercloud which, even if it "come nigh enough to strike, yet being deprived of its fire, it cannot."

10. The first conception of the lightning rod, as a point discharger, followed immediately; "I say, if these things are so, may not the knowledge of this power of points be of use to mankind in preserving houses, churches, ships, etc. from the stroke of lightning, by directing us to fix on the highest parts of these edifices, upright rods of iron made sharp as a needle, and gilt to prevent rusting, and from the foot of these rods a wire down the outside of the building into the ground, or down one of the shrouds of a ship and down her side until it reaches the water? Would not these pointed rods probably draw the electric fire silently out of a cloud before it came nigh enough to strike, and thereby secure us from that most sudden and terrible mischief?" (**27**).

Elsewhere in the same year, 1750, he suggested that "if . . . on the tops of weathercocks, vanes or spindles of churches, spires or masts, there should be put a rod of iron 8 or 10 feet in length, sharpened gradually to a point like a needle, and gilt to prevent rusting, or divided into a number of points, which would be better—the electrical fire would, I think, be drawn out of a cloud silently, before it could come near enough to strike; only a light would be seen at the point, like the sailor's corpusante." (**28**).

11. In June 1751 Franklin commented with interest on a detailed account by a Captain Waddell on the electrical effects on his ship of a storm at sea. Waddell reported enormous glows, or "corpusantes," at the mastheads, which "burnt like very large torches," but these certainly did *not* discharge the cloud completely, for the ship was struck by lightning. In his comment Franklin says "had there been a good wire communication from the spintle-heads to the sea . . . I imagine there would have been no stroke; or if a stroke, the wire would have conducted it all into the sea without damage to the ship." (**29**).

From this time onwards, while still holding that one function of the lightning rod was to discharge the cloud silently, he always added its alternative function of disposing safely of any stroke which came to it.

In 1753 he wrote "Metalline rods, therefore, of sufficient thickness and extending from the highest part of an edifice to the ground . . . will, I think, secure the building from damage, either by restoring the equilibrium so fast as to prevent a stroke, or by conducting it in the substance of the rod as far as the rod goes." (**30**).

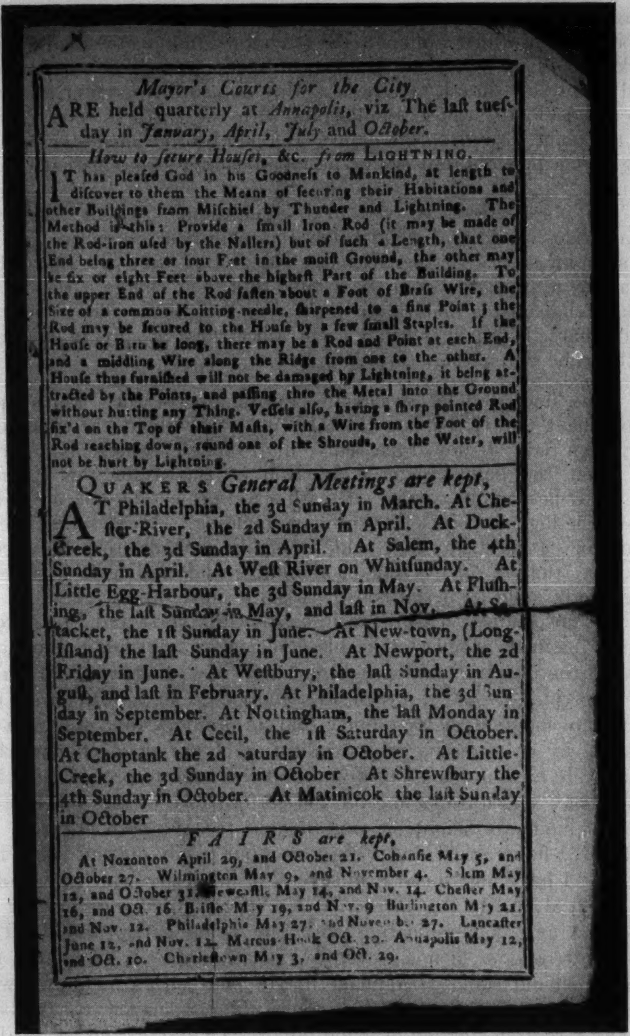
He had one final remark to make on the point-discharge function of the rod. "An eye so situated" he wrote in 1753, "as to view horizontally the under-side of a thundercloud will see . . . a number of petty clouds, one under another, the lowest sometimes not far from the earth. These, as so many stepping-stones, assist in conducting a stroke between the cloud and a building." (**31**). He then described an experiment in which a linked series of charged fragments of loose cotton locks could be progressively discharged by a point held below the lowest and as a result shrank together. "May not, in like manner, the small electrised clouds, whose equilibrium with the earth is soon restored by the point, rise up to the main body, and by that means occasion so large a vacancy, as that the grand cloud cannot strike in that place?" (**31**).

The observation involved in this ingenious account is correct; small wisps of charged cloud below the main base do on occasion act as stepping-stones to the discharge (**32**). But they are charged by ions moving upwards from the ground and their charge is opposite in sign to that on the main lower portion of the cloud. They could not be discharged by points below them, since these are giving off charge of the same sign as they carry.

12. The unexpectedly successful performance of the "Philadelphia Experiment" in 1752 made Franklin uncertain about the need for a very high rod. It now appeared to him, though wrongly as it turned out, that the point-discharge function envisaged for the lightning rod *might* perhaps be carried out with a rod projecting only a few feet above the highest point of an ordinary building. At the same time his laboratory experiments had made it highly probable that the second function (that of "attracting" a discharge and leading it harmlessly to ground) could be performed by a rod of moderate height.

This uncertainty, which, as will be shown in §§ 15 and 16 was completely justified, is reflected in his first general and public announcement of the invention of the lightning rod (in *Poor Richard's Almanac* for 1753, publication of which was announced in 1752), for in this he did not mention the possibility that an ordinary rod could prevent a stroke by point-discharge neutralisation of the cloud charge. Unfortunately for him his scientific caution was misinterpreted and when no evidence was forthcoming for the performance of this function by a rod of moderate height, he was thought to have been in error.

In 1755 he wrote "I find I have been but partly understood in this matter. I have mentioned it in several of my letters and except once [see § 10] always in the *alternative, viz.* that pointed rods erected on buildings, and communicating with the moist earth, would either *prevent* a stroke, *or,* if not prevented, would *conduct* it, so as that the building should suffer no damage." He went on to point out with unusual heat that the second function of the rod seemed to have been "totally forgotten, though of equal importance and advantage." The very instances adduced by him "to show that the rods had protected houses, by *conducting* the lightning *when there was a stroke* . . . are said to be instances of conductors being *unsuccessful*" (**33**).



Mayor's Courts for the City

ARE held quarterly at *Annapolis*, viz The laſt tueſday in *January*, *April*, *July* and *October*.

How to ſecure Houſes, &c. *from* LIGHTNING.

IT has pleaſed God in his Goodneſs to Mankind, at length to diſcover to them the Means of ſecuring their Habitations and other Buildings from Miſchief by Thunder and Lightning. The Method is this: Provide a ſmall Iron Rod (it may be made of the Rod-iron uſed by the Nailers) but of ſuch a Length, that one End being three or four Feet in the moiſt Ground, the other may be ſix or eight Feet above the higheſt Part of the Building. To the upper End of the Rod faſten about a Foot of Braſs Wire, the Size of a common Knitting-needle, ſharpened to a fine Point; the Rod may be ſecured to the Houſe by a few ſmall Staples. If the Houſe or Barn be long, there may be a Rod and Point at each End, and a middling Wire along the Ridge from one to the other. A Houſe thus furniſhed will not be damaged by Lightning, it being attracted by the Points, and paſſing thro the Metal into the Ground without hurting any Thing. Veſſels alſo, having a ſharp pointed Rod fix'd on the Top of their Maſts, with a Wire from the Foot of the Rod reaching down, round one of the Shrouds, to the Water, will not be hurt by Lightning.

QUAKERS *General Meetings are kept*,

AT Philadelphia, the 3d Sunday in March. At Cheſter-River, the 2d Sunday in April. At Duck-Creek, the 3d Sunday in April. At Salem, the 4th Sunday in April. At Weſt River on Whitſunday. At Little Egg-Harbour, the 3d Sunday in May. At Fluſhing, the laſt Sunday in May, and laſt in Nov. At Setacket, the 1ſt Sunday in June. At New-town, (Long-Iſland) the laſt Sunday in June. At Newport, the 2d Friday in June. At Weſtbury, the laſt Sunday in Auguſt, and laſt in February. At Philadelphia, the 3d Sunday in September. At Nottingham, the laſt Monday in September. At Cecil, the 1ſt Saturday in October. At Choptank the 2d Saturday in October. At Little-Creek, the 3d Sunday in October At Shrewſbury the 4th Sunday in October. At Matinicok the laſt Sunday in October

FAIRS are kept,

At Noxonton April 29, and October 21. Cohanſie May 5, and October 27. Wilmington May 9, and November 4. Salem May 12, and October 31. Newcaſtle May 14, and Nov. 14. Cheſter May 16, and Oct. 16. Briſtol May 19, and Nov. 9. Burlington May 21. and Nov. 12. Philadelphia May 27. and November 27. Lancaſter June 12, and Nov. 12. Marcus-Hook Oct. 10. Annapolis May 12, and Oct. 10. Charleſtown May 3, and Oct. 29.

The first public announcement of the lightning rod in *Poor Richard's Almanac* for 1753.

13. From 1752 onwards many "Franklin rods" were erected in various parts of the American colonies and the device passed from its pilot stage into practical use. In 1760 a rod saved the house of Mr. West of Philadelphia from serious damage by a direct discharge and soon afterwards other proofs of its utility appeared. Franklin was constantly considering the specifications needed for a successful installation. Some minor damage to Mr. West's house near the base of the rod he correctly ascribed to inadequate earthing—"the rod should have been sunk deeper, till it came to earth moister and therefore apter to receive and dissipate the electric fluid" (**34**). The quarter-inch thickness of the rod, he noted, seemed to have been enough but he was inclined to think from other reports "that larger may be sometimes necessary."

Of this first success of his rod he wrote to Kinnersley "Indeed, in the construction of an instrument so new, and of which we could have so little experience it is rather lucky that we should at first be so near the truth as we seem to be, and commit so few errors." (**34**).

His final "specification" for the rod, after considering many reports, was written from Paris in 1767 (**35**). With an earlier comment in 1760 it covered the following points:

(*a*) tall trees and buildings by themselves are not good conductors and are often damaged by lightning, but buildings roofed with metal and with metal drainpipes "continued into the ground" are perfectly safe;

(*b*) the iron rod should project six to eight feet above the highest part of the building, tapering to a fine gilded point to prevent rusting. In the case of a large building two or more rods may be placed at different points for greater security;

(*c*) the lower end of the rod should penetrate 2 to 3 feet into moist ground or better be bent under the surface for 6 to 8 feet to enter the ground away from the foundations, which may be dry;

(*d*) the diameter of the rod need not exceed half an inch; thinner rods have proved effective. The rod can be fastened to the building with iron staples;

(*e*) the rod should be continuous and not made up of links or parts hooked together;

(*f*) even in England, where lightning is not very frequent, there are many exposed buildings and people are afraid of lightning; it may therefore be worthwhile installing conductors because by relieving "painful apprehensions" of damage one might "contribute more to the happiness of mankind" than direct protection itself might do;

(*g*) for safety in a house during a storm he advised the timid to keep away from chimneys and metal objects (and to be quite free from danger, to take refuge in a "hammock or swinging bed suspended by silk cords" in the centre of the room).

These statements form the major part of modern codes of lightning protection, though copper is more generally used than iron for the conductors and points are not always insisted on.

Franklin's last scientific discussion of the lightning rod was written in 1768 in reply to a criticism by the Abbé Nollet that "all these iron points that are being put up into the air . . . are more likely to attract lightning than to save us from it" (**36**). After criticising the Abbé's uncertain and evasive position on the practice of ringing church bells to disperse thunderstorms, he said "One would think it was now time to try some other trick; and ours is recommended (whatever this able philosopher may have been told to the contrary) by more than twelve years' experience, wherein, among the great number of houses furnished with iron rods in North America, not one so guarded has been materially hurt with lightning, and several have been evidently preserved by their means; while a number of houses, churches, barns, ships, etc. in different places, unprovided with rods, have been struck and greatly damaged, demolished or burnt." (**37**).

14. The opposition of certain European men of science to pointed lightning conductors, and in particular of the Abbé Nollet of Paris and Benjamin Wilson of the Royal Society, was very strong. Wilson, like Nollet, thought that pointed rods "may be promoting the very mischief we mean to prevent." He was in favour of blunted conductors as likely to be equally effective. The great controversy of "knobs versus points" which followed has been fully described elsewhere (**37**). Franklin's original conception of the rod as a dissipator of the cloud charge was strongly attacked and, as has been seen (§ 12) the fact that he had himself emphasised its second function and had suggested a very high rod for its first function, tended to be ignored.

It is difficult to prove a negative; in Franklin's lifetime no evidence could be adduced either that a flash had *not* struck a rodded building because the points on it had discharged the cloud or that a flash which *had* struck a building (and been safely conducted away), might have struck somewhere else if the rod had not attracted it. From the practical and economic points of view this was of little consequence, since rods certainly did *not* "promote the very mischief we mean to prevent." But the answers to the scientific questions involved in the controversy have had to await the results of fairly recent investigations.

IV. MODERN KNOWLEDGE OF THE FUNCTIONS OF THE LIGHTNING RCD

With the significant exception of first strokes to very high structures, which will be discussed in the next section, it is now known that the lightning discharge to ground takes place in two stages (**38**, **41**). In the first of these, a downward-moving leader streamer, which carries negative charge on its conducting channel and branches, lowers electricity from the part of the cloud tapped by it into the air and places it closer to the ground than it was before. This produces an exceptionally strong electric field between the tip of the advancing leader and the earth. When the tip is near enough to the ground the second or return stage takes place; a positive streamer of great intensity then rushes upwards from some projection on the ground to effect a junction with the leader and pass its negative charge to earth. The length of this streamer will mainly depend on the height of the projection from which it starts. A lightning conductor on a house, owing to the concentration of electric field between its tip and that of the approaching leader, may produce a streamer some fifty feet long and this effectively draws the discharge to the rod. The protective value of the lightning conductor lies in this ability to produce a longer junction-streamer than any lower projection, such as a chimney, in its neighborhood and to carry safely to earth the heavy current in the return stage of the discharge.

In performing this, its second, function, there is no reason to suppose that sharp points at the end of the rod have any appreciable effect upon this length of the streamer and hence on the radius of protection afforded by the rod. Glows and streamers are produced in the laboratory more easily from sharp points than from blunt rods, but on the scale found in the lightning discharge, the blunt top of any rod must be considered as very nearly equivalent to a needle-point.

15. For very high rods, like those surmounting the Empire State Building or the Washington Memorial, however, the description just given does not always apply. It has been shown that the first of the series of strikes which usually make up a flash to the Empire State Building is in most cases an upward-moving positively-charged streamer from the rod. The streamer travels the whole way to the cloud and discharges a portion of it by enabling a long-continuing current to flow down its channel (39).

This observation would have delighted Franklin, for it is exactly the effect he predicted and which was denied by his contemporaries in the controversy about pointed rods. Here is his "tall tower or steeple" equipped with an earthed rod and drawing the electric fire down *silently*, for the process is not followed by a rapid or brilliant return stage and cases of lightning without appreciable thunder have been reported from the Washington Monument. Although it has been found that subsequent strokes of the same flash to the Empire State Building (as is the case so far as we know with all discharges to lower buildings) require the double leader-return stroke process, it is clear that after nearly two hundred years, when a really very high rodded building was available for the trial, the controversial first function of Franklin's rod was brilliantly established.

16. To fulfil this function, however, the rod has to be very long. The usual lightning rod, less than a hundred feet high, does not cause a sufficient concentration of field at its tip for a positive streamer to pass all the way to the cloud. It is effective only after the field at its tip has been very much enhanced by the downward movement of the leader streamer from the cloud.

Its first, or point-discharge, function is therefore quite minor;

though point-discharge current flows from it most of the time the cloud is overhead, this current is of the order of micro-ampères only.

The *total* effect of all the projecting points on trees, buildings and bushes below a cloud does, however, add up to a continuous current of several ampères and a current of the same order has recently been found by flights over the positively-charged tops of thunderclouds to flow from the cloud to the conducting upper air (**40**). This external circuit is completed by a flow of current, of small density but extending over a large area, between upper air and earth in fine-weather regions (**41**).

Discharging points *en masse* thus act in the manner suggested by Franklin for single points, by placing a considerable load on the charge-generating mechanism of the thunderstorm, though lightning rods at ordinary heights do little to increase it. Evidence of the effect of the external load has been obtained from studies of the rate of recovery of the field, and so of the charges, produced by a cloud after a flash has taken place within it. These show that the point-discharge load is a significant factor in reducing the rate at which the charges are re-established and hence the rate at which cloud discharges occur (**41**). But there is at present no evidence that it prevents lightning discharges to ground or even cuts down the frequency of this type of discharge.

On the contrary, there is reason to think that the upward-moving positive ions produced by point-discharge are collected by drops in the base of the cloud (and by the wisps of cloud below the base which were observed by Franklin to act as stepping-stones to the discharge) and actually trigger off negative discharges to ground in cases where they might otherwise not have occurred (**32**).

17. The second function of the rod, to attract the discharge and convey it harmlessly to earth is now universally recognised. Its various applications and its effectiveness are to be more fully discussed in another contribution to this volume. All that need be said of it here is that Franklin's specifications for the rod, summarised in § 13, and his surmise that a rod projecting six to eight feet above the chimney of the average house of his day would afford adequate protection, have proved substantially correct.

V. FRANKLIN'S GENERAL INTEREST IN LIGHTNING PROBLEMS

18. The matters discussed in the preceding paragraphs of this paper by no means exhaust the list of Franklin's investigations and ideas on lightning and thunderstorms. He was indefatigable in following up every bit of knowledge and performing every experiment which could illuminate the subject, and when he was wrong in his interpretations he was quick to correct them with "noble frankness" (**13d**). Thus, when Kinnersley wrote to him that an experiment Franklin had proposed before he left Philadelphia had shown that the electric discharge melted metals by heat, and not "by a cold fusion as we formerly supposed" he was delighted with this "beautiful experiment" and blamed himself for "building an hypothesis on anything but clear facts and experiments" (**42**).

He kept himself constantly informed on the details of damage to buildings by lightning so as to be able to reconstruct what had actually occurred. His lively imagination was always at work in devising explanations of queer happenings related to thunderstorms and experiments to test these explanations. He correctly explained the way trees could be shattered by lightning by the sudden and explosive evaporation of the water in the sap (**43**). A case of reversal of the polarity of a ship's compass by a lightning discharge he showed by experiment to have been due to the magnetisation of some nearby nails in the binnacle (**44**).

Perhaps his most prophetic and imaginative idea was to infer the existence of the ionosphere from the Aurora Borealis, which he thought might well be due to electric currents in the upper air—"Who knows but there may be, as the Antients thought, a region of this fire above our atmosphere, prevented by our air, and its own too great distance for attraction, from joining our earth." (**45**).

19. Since this article is concerned with Franklin's work on thunderstorm electrification and the lightning rod only, it cannot claim to have done more than try to show in some detail how he proceeded in this field from experiment to experiment and from idea to idea until he reached the culminating experiment which is commemorated this year. Franklin's other contributions to science and particularly to fundamental electrical knowledge were very great, but the thunderstorm problem was the chief one he set himself—and his group of friends—to solve and thereby "to produce something of use to mankind." In its solution he overcame difficulties of technique and thought which had baffled his better-equipped predecessors and contemporaries; the honours showered upon him afterwards by scientific academies in Europe were richly deserved. If he was disappointed in the "envy, robbery and abuse" in which subsequent controversy involved him and seemed to regard it as a chapter in his life worth no more than casual mention in his autobiography, this may well have been because he was intensely proud of it and of the enthusiastic if poorly equipped team of four men of Philadelphia which he had led to such high success. Perhaps too, he knew that he would one day be bracketed (**46**) in history with Laplace, Huyghens and Newton and was content that he had "found electricity a curiosity and left it a science" (**47**).

REFERENCES

(1) E.g. *Encyclopædia Brittanica*, Eleventh Ed., 1910/11 Art. "Benjamin Franklin."

(2) "Benjamin Franklin's Experiments" edited, with a critical and historical introduction by I. BERNARD COHEN, Harvard University Press, 1941.

(Since it is very difficult to trace references in the series of letters which make up Franklin's own book, most of the following references are taken from Dr. Cohen's work, the pages of which are indicated by a number following the letter C. I gratefully acknowledge my debt to Dr. Cohen's book.)

(3) C. 170.
(4) C. 175 and 213.
(5) C. 199.
(6) C. 129.
(7) C. 172.
(8) C. 216/7, 225.
(9) C. 218.
(10) C. 219/20
(10a) All Franklin's experiments were known abroad as "Philadelphia Experiments," but he himself (C. 265) referred to this as *the* "Philadelphia Experiment."
(11) C. 219.
(12) C. 222.
(13) **(a)** C. 100–104, C. 257–264; **(b)** "The Flight of Thunderbolts," by B. F. J. SCHONLAND, Ch. II, Oxford University Press, 1950; **(c)** "Benjamin Franklin," by CARL VAN DOREN, p. 161 ff., Putnam, 1939; **(d)** "The History and Present State of Electricity," by JOSEPH PRIESTLY, London, 1767, p. 327 ff.
(14) C. 350/1.
(15) Ref. **13(c)**, p. 167, C. 268.
(16) C. 268/9.
(17) C. 270/1 and 280.
(18) C. 271, 281, 351.
(19) C. 201/6.
(20) C. 267.
(21) C. 268 and 318.
(22) C. 272–276.
(23) C. 359.
(24) C. 334.
(25) C. 207.
(26) C. 220/1.
(27) C. 221.
(28) C. 86.
(29) C. 242.
(30) C. 277.
(31) C. 279.
(32) D. J. MALAN AND B. F. J. SCHONLAND, *Proc. Roy. Soc. A*, Vol. 209, p. 158 (1951).
(33) C. 308.
(34) C. 372/3.
(35) C. 390/2.
(36) C. 394/5 (my translation).
(37) C. 135 ff., refs. **13(b)**, **13(c)**.
(38) Ref. **13(b)**.
(39) K. B. MCEACHRON, JOUR. FRANKLIN INST., Vol. 227, p. 149 (1939).
(40) O. H. GISH AND G. R. WAIT, *Jour. Geophys. Res.*, Vol. 55, p. 473 (1950).
(41) References in "Atmospheric Electricity," by B. F. J. SCHONLAND, Methuen (Lond.) 1932 (second edition printing).
(42) C. 370/1.
(43) C. 373/4.
(44) C. 321.
(45) C. 324.
(46) R. A. MILLIKAN in "Meet Dr. Franklin," p. 13, The Franklin Institute (1943).
(47) CARL VAN DOREN, ref. **13(c)**, p. 169.

PREJUDICE AGAINST THE INTRODUCTION OF LIGHTNING RODS *

BY

I. BERNARD COHEN ‡

"How astonishing is the force of prejudice even in an age of so much knowledge and free inquiry," wrote Professor John Winthrop of Harvard College to Benjamin Franklin on 6 January 1768,[1] after having read in the *Philosophical Transactions* of the Royal Society of London an account of the destructive effects of lightning on St. Bride's steeple. "It is amazing to me, that after the full demonstration you had given, of the identity of lightning and of electricity, and the power of metalline conductors, they should ever think of repairing that steeple without such conductors."

The celebration of the two hundredth anniversary of the successful demonstration that the lightning discharge is an electrical phenomenon, and the practical introduction of lightning rods, provides an occasion to examine into the prejudices which prevented the rapid introduction of lightning rods in Europe and in America. All too often, we tend to think of the history of scientific thought as an orderly process, one in which proofs are convincing and have the effect of rapidly altering men's minds. The history of science and the history of technology both show, however, that there is always a considerable inertia to the human mind which tends to prevent the acceptance of new ideas or the introduction of new instruments. In 1752 experiment confirmed the hypothesis of "the identity of lightning and of electricity," with the attendant corollary that lightning would therefore be attracted by pointed metallic conductors and could be safely conducted into the ground. Looking backward from today, we are apt to suppose—as Winthrop did almost two centuries ago—that the new invention would have been given a warm reception and that thenceforth people all over the world no longer need have trembled with fear at the onset of a thunderstorm. While a number of lightning rods were introduced in various parts of the world in the late 18th century, the record of history provides a large number of instances of refusal to make use of this new device to prevent the lightning destruction.

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‡ Harvard University, Cambridge, Mass.

[1] Franklin published an extract from this letter in the fourth and fifth editions of his book on electricity (London: 1769, 1774). See *Benjamin Franklin's experiments, a new edition of Franklin's "Experiments and observations on electricity,"* edited with a critical and historical introduction by I. Bernard Cohen (Cambridge: Harvard University Press, 1941), p. 393.

It is instructive for us to review some aspects of the opposition to lightning rods, because we may see in the very variety of reasons advanced against their use the normal resistance to change which is characteristic of the human mind, and the ways in which prejudice tends to prevent radical departures from accepted patterns of behavior, however convincing the evidence may be that the customary practices are useless or even dangerous.

LIGHTNING RODS *VERSUS* CHURCH BELLS

In reply to Winthrop's letter about the force of prejudice preventing the adoption of lightning rods, Franklin explained that to him it did not seem quite so extraordinary that "unlearned men, such as commonly compose our church vestries" should be unacquainted with the benefits of lightning rods, or that they should still be prejudiced against the use of them, "when we see how long even philosophers, men of extensive science and great ingenuity, can hold out against the evidence of new knowledge that does not square with their preconceptions; and how long men can retain a practice that is conformable to their prejudices, and expect a benefit from such practice, though constant experience shows its inutility."[2]

When Franklin wrote about men retaining a practice conformable to their prejudices, he had in mind the ringing of church bells during a lightning storm. The practice of ringing church bells to dissipate lightning storms and prevent their deleterious effects had a long tradition in Europe and had been a concomitant to the general belief in the diabolical agency manifested in storms.[3] Many a church bell bore an inscription testifying to the use it might have in dissipating the effects of thunder and lightning. The ritual of Paris for consecrating bells declared that "whensoever this bell shall sound, it shall drive away the malign influences of the assailing spirits, the horror of their apparitions, the rush of whirlwinds, the stroke of lightning, the harm of thunder, the disasters of storms, and all the spirits of the tempest."[4] Typical inscriptions on church bells described their power to "ward off lightning and malignant demons"; stated that "the sound of this bell vanquishes tempests, repels demons, and summons men," or "praise God, put to flight the clouds, affright the demons, and call the people"; or noted that "it is I who dissipate the thunders."[5] A form of inscription, denoting the many uses of bells, has been made famous through Schiller's poem *Die Glöcke;* it reads:

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[2] Franklin's reply to Winthrop may be found in *Benjamin Franklin's experiments* (ref. 1), pp. 393–398.

[3] According to Andrew Dickson White, *A history of the warfare of science with theology in Christendom* (New York & London: D. Appleton and Company, 1928; preface dated 1894), vol. 1, p. 344, ". . . the means of baffling the powers of the air which came to be most widely used was the ringing of consecrated church bells. This usage had begun in the time of Charlemagne. . . ."

[4] Quoted by White (ref. 3), vol. 1, p. 347. When Franklin published his letter to Winthrop in the fourth edition of his book on electricity, he included a portion of the *oraisons* used "suivant le rituel de Paris, lorsqu'on bénit des cloches," which he had copied from an article of the Abbé Nollet, "Mémoire sur les effets du tonnerre comparés à ceux de l'électricité; avec quelques considérations sur les moyens de se garantir des premiers," *Histoire de l'Académie Royale des Sciences*, "mémoires," 408–451, 1764.

> *Deum laudo, vivos voco,*
> *Mortuos plango, fulgura frango.*[6]

Despite the sanction given in Catholic countries to the use of bells as a means of preventing the effects of lightning,[7] the fact was notorious by the 18th century that many churches were struck by lightning bolts and that many bell ringers were killed during lightning storms. In his reply to Winthrop, Franklin drew special attention to the well-known danger in attempting to use bells to ward off the effects of lightning. Franklin had been more than a little annoyed by a paper of the Abbé Nollet, published in the memoirs of the Royal French Academy of Sciences, in which he had objected to the use of metal conductors outside a building as useless or dangerous. Nollet had given many examples of the effects of lightning in churches (as well as other buildings) in which, as Franklin pointed out, the lightning "was conducted from one part [of the building] to another by wires, gildings, and other pieces of metal that were within, or connected with the building. . . ." Among the evidence cited by the Abbé Nollet was a report of M. Deslandes of 1718, describing a storm on the night of the 14th of April in which lightning had struck 24 churches between Landernau and Saint Pol-de-Léon in Brittany; the churches struck by the lightning were the very ones in which the bells had been ringing, while the lightning had apparently spared those churches in which the bells had been silent; one church had been entirely destroyed and two of the four bell-ringers had been killed.[8]

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[5] Quoted by White (ref. 3), p. 345. A 16th century-account of a bell consecration relates how the Bishop "sayde certen Psalmes, [and afterwards] he consecrateth water and salte, and mingleth them together, wherwith he washeth the belle diligently both within and without, after wypeth it drie, and with holy oyle draweth in it the signe of the crosse, and prayeth God, that whan they shall rynge or sounde that bell, all the disceiptes of the devyll may vanyshe away, hayle, thondryng, lightening, wyndes, and tempestes, and all untemperate weathers may be aswaged." *Ibid.*, p. 346.

[6] Cf. I. Bernard Cohen, editor, *Benjamin Franklin: a letter on lightning rods* (Cambridge, 1942).

[7] White (ref. 3, *supra*), pp. 347–349, offers evidence concerning the continuance in Protestant Germany of the belief that church bells might drive away tempests. They were rung for this purpose at least once in the 20th century in England. Although the custom existed in Catholic countries in the 18th century, and in some even in the 19th, many officials of the 18th-century Catholic Church—including Pope Benedict XIV (see the section in this article "A Pope and a priest attempt to introduce lightning rods")—advocated the use of lightning rods.

In Hasting's *Encyclopaedia of religion and ethics* (New York: Charles Scribner's Sons, 1928), vol. 6, p. 315, it is postulated that at first the bells had been rung on the occasion of a violent storm in order to call the people together to pray for their mutual protection; then, supposedly, over the course of time, the original purpose was lost and the bells were rung during storms without any assembling of the populace for prayer; the Devil, in other words, became vulnerable to the bells themselves and prayers were no longer needed to combat his storms. This idea does not seem well founded. It supposes that the Devil underwent a conditioning, like Pavlov's dogs, to the ringing of bells. Nor does it account for the prevalence of the custom of bell-ringing in storms among primitive people, nor of the custom in modern Europe of firing cannons to dissipate lightning as well as ringing bells. More likely, the origin of the practice has traces of "sympathetic magic" in that storms, which are noisy disturbances in the atmosphere (produced by demons or the "powers of the air") are supposed to be counteracted by a ritual in which bells were rung (or, later, cannons fired) producing a similar noisy disturbance in the air.

Nollet, Franklin wrote, "cautions people not to ring the church bells during a thunder-storm, lest the lightning, in its way to the earth, should be conducted down to them by the bell ropes." Nollet's remarks on this score follow:

> Bells, by virtue of their benediction, should scatter the thunder-storms and preserve us from strokes of lightning; but the church permits human prudence the choice of the times when it is suitable to use this preservative. I do not know whether sound, considered physically, is capable or not of making a thunder-cloud burst and of causing the discharge of its fire towards terrestrial objects; but it is certain and proved by experience that thunder can fall on a bell-tower whether one is ringing it or whether one isn't; and if that happens in the first case, the bell ringers are in great danger, because they pull the cords by which the commotion of the lightning can be communicated to them: it is therefore much wiser to let the bells be silent when a thunder-cloud comes over the church.[9]

Since Nollet had carefully observed the path of lightning when buildings were struck, Franklin found it difficult to understand why he did not advocate the use of lightning rods.[10] For, as Franklin noted, if the lightning on its way to earth could be conducted down the bell ropes which are bad conductors, would it not be wise to offer the lightning a path through good metal conductors placed outside of the steeple, that is, lightning rods? The lightning would certainly "choose to pass in" the good metal conductor or the rod, "rather than in [the] dry hemp," of the bell rope. The expectation "that the sound of such blessed bells would drive away those storms, and secure our buildings from the stroke of lightning" had not been realized during more than a thousand years of experience, Franklin noted, while "lightning seems to strike steeples of choice, and that at the very time the bells are ringing; yet they still continue to bless the new bells, and jangle the old ones whenever it thunders." One would think, wrote Franklin, "it was now time to try some other trick;—and ours is recommended (whatever this able philosopher [Nollet] may have been told to the contrary) by more than twelve years experience, wherein, among the great numbers of houses furnished with iron rods in North America, not one so guarded has been materially hurt with lightning, and several have been evidently preserved by their means; while a number of houses, churches, barns, ships, &c. in different places, unprovided with rods, have been struck and greatly damaged, demolished, or burnt."

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[8] Quoted by Franklin (in his letter to Winthrop) from the article of Nollet (ref. 4, *supra*). The original account of Deslandes is summarized in *Hist. de l'Ac. R. des Sc.*, "histoire," 21–22, 1719.

According to Deslandes, the people believed that the reason the bell-ringing churches were struck was that the day was Holy Friday, when it is forbidden to ring church bells. The Rt. Rev. Monsignor John Walsh [*The mass and vestments of the Catholic Church* (New York, etc.: Benziger Brothers, 1916), p. 339] states that according to Pope Benedict XIV, the bells are stilled from the "Gloria" in the Mass of Holy Thursday until the "Gloria" on Holy Saturday "because bells typify the preachers of the word of God and all preaching was silenced during the trial and passion of Our Lord."

[9] Lord Bacon had noted that "it is believed by some, that great ringing of bells in populous cities hath chased away thunder, and also dissipated pestilent air: all of which may be also from the concussion of the air, and not from the sound." See "Natural History," Cent. 2, 127, *Works of Francis Bacon*, coll. and ed. by James Spedding, Robert Leslie Ellis, and Douglas Denon Heath (Boston: Brown & Taggard, 1862), vol. 4, p. 240.

In the *Encyclopédie* of Diderot and D'Alembert (*s. v.* Tonnerre), we find the statement that "thunder can be disrupted and diverted by the sound of several bells or the firing of a cannon; thereby a great agitation is excited in the air which disperses the parts of the thunder. . . ." This was written by the eminent Dutch physicist, Peter van Musschenbroek (discoverer of the Leyden jar); he warned that the bells should never be rung when the clouds were exactly overhead, since then there would be great danger. Musschenbroek repeated these ideas in his oft-reprinted survey of physics [e. g., the French edition, *Essai de physique*, trad. du hollandois par Pierre Massuet (Leyden: Samuel Luchtmans, 1751), tome 2, p. 846: ch. XL, "Des météores ignés," §1732]; it is interesting to note that although Musschenbroek believed in the physical action of bells to counteract lightning, he indicated the incorrectness of the view that held thunder and lightning to be "un effet du Démon & autres malins Esprits."

In all probability, Franklin argued, the vestries of "our English churches" were not well acquainted with the facts. Otherwise, as "good Protestants they have no faith in the blessing of bells, [and] they would be less excusable in not providing this other security for their respective churches, and for the good people that may happen to be assembled in them during a tempest, especially as those buildings, from their greater height, are more exposed to the stroke of lightning than our common dwellings." Franklin was being much more generous than the facts in the situation of St. Bride's warranted. When he wrote his letter to Winthrop in 1768, he must surely have known that the spire on St. Bride's Church in London, destroyed by lightning in 1764, had previously been destroyed by the same cause in 1750. The destruction of 1764 was rendered particularly interesting in that it served as the basis of a report by William Watson, published in Volume 54 of the *Philosophical Transactions* of the Royal Society, in which the path of the lightning in St. Bride's was examined in the greatest of detail. In the same volume of the *Philosophical Transactions*, two other papers on lightning appeared; one, by E. Delaval, who also reported extensively on the damage caused to St. Bride's, and the other by Benjamin Wilson.[11] While these three authors may have disagreed somewhat on details of construction of the rods, there was no question of their unanimous recommendation of some form of lightning conductors as a preservative for this and similar structures. The conclusion to the affair has been described in Priestley's history of electricity: "My readers at a distance from London will hardly believe me, when I inform them, that the elegant spire which has been the subject of a great part of this section, and which has been twice damaged by lightning (for it is now very probable, that a damage it received in the year 1750, was owing to the same cause) is now repaired, without any metallic conductor, to guard it in case of a third stroke." [12] Can the vestry of the Church of St. Bride's have remained wholly ignorant of the discussion of the fate of their spire by the leading scientific body of the realm?

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[10] Nollet's objections to lightning rods are described at further length in the section of this article entitled "The action of lightning rods—to attract or prevent a stroke?"

[11] Cf. B. F. J. Schonland, *The flight of thunderbolts* (Oxford: Clarendon Press, 1950), p. 25. For those interested in further reading on the whole subject of lightning and the history of our knowledge of this phenomenon, Schonland's book cannot be too highly recommended.

After the damage to St. Bride's, the Dean and Chapter of St. Paul's asked the Royal Society in March 1769 for advice on protecting their church from lightning. Franklin was a member of the committee, along with Watson, Delaval and Wilson, and John Canton. It was recommended that a form of lightning rod be installed; that is, that a "complete metallic communication [be made] between the cross placed over the lanthorn and the leaden covering of the great dome [which was grounded through the water pipes]; as from its height, if any lightning struck it, it would most probably affect the cross." [13]

It may be thought that this episode marked the end of British ecclesiastical resistance to Franklin's invention. That such was not the case may be seen in the preface (dated 1 May 1843) to the remarkable book on lightning and rods written by Sir William Snow Harris:

> The beautiful spire of St. Martin's church, in London, has been recently rebuilt, at a cost of full one thousand pounds sterling, in consequence of an explosion of lightning, which fell on it in July last. Brixton church, near London, had also to undergo extensive repairs, rendered necessary from the same cause. In January, 1841, the spires of Spitalfields and Streatham churches, were struck by lightning, and the latter nearly destroyed: and in August of the same year an electrical discharge shook the spires of St. Martin's and St. Michael's churches, at Liverpool, both modern edifices of a costly and elaborate construction. In January, 1836, the spire of St. Michael's church, near Cork, was rent by lightning down to its very base; and in the following October the magnificent spire of Christ church, Doncaster, was almost totally destroyed by a similar discharge.
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> Thus, in the United Kingdom alone, and within the short space of five years, we find at least eight churches to have been either severely damaged or partially demolished by lightning; to this list of casualties may be added the fine old church of Exton, in Rutland, which, according to the public journals, was in great measure destroyed in a thunderstorm, so lately as the 25th of last April. A writer in Nicholson's *Journal of Science*, states that he has made a calcu-

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[12] Joseph Priestley, *History and present state of electricity* (London: C. Bathurst, & c., 1775), ed. 3, vol. 1, p. 472.

[13] Cf. Charles Richard Weld, *A history of the Royal Society* (London: John W. Parker, 1848), vol. 2, ch. 4. The committee dodged the issue, which arose soon afterwards, between B. Wilson and the others as to whether the rods on buildings should be blunt or pointed, or whether they should project above the building. On this score, see the section of this article, *infra*, entitled "The action of lightning rods—to attract or prevent a stroke?"

> lation of the average annual amount of damage done by lightning in England alone, and that it cannot be far short of fifty thousand pounds.[14]

Although opposition did not cease at once, religious prejudice against lightning rods did abate, even in the 18th century. St. Mark's in Venice provides an example. Despite "the angel at its summit and the bells consecrated to ward off the powers of the air," its steeple had been frequently struck and injured or ruined by lightning—in 1388, in 1417, in 1489, in 1548, 1565, 1653, and again in 1745. The tower was badly struck in 1761 and again in the following year. In 1766 (fourteen years after Franklin's discovery of the lightning rod), a lightning rod was finally placed upon it; in 1894 Andrew D. White was pleased to report that "it has never been struck since."[15]

Today, a church with lightning rods upon spire or tower is a familiar sight. Just a century ago, however, bells were still being rung in an attempt to prevent the destructive effects of the lightning discharge. One of the most dramatic accounts of a tragic attempt to dissipate a lightning storm is recorded for us by the famous Spanish physiologist Santiago Ramón y Cajal in his autobiography:

> The second event to which I referred, namely, the striking of the school by lightning, with extraordinarily dramatic results, also left a broad stamp upon my memory. For the first time there appeared to me in all its irresistible majesty, that blind and ungovernable force of the universe, which is indifferent to suffering and seems not to distinguish between the innocent and the guilty.
>
> This was the tragic occurrence. We children were assembled one afternoon in the school, engaged in prayers under the leadership of the mistress (the master being confined to bed that day). When the afternoon was already advanced, the sky became rapidly overcast and there were several violent thunder-claps, which did not alarm us; then suddenly, in the midst of the deep abstraction of the prayer, our lips in the act of uttering the words of supplication: "Lord deliver us from all evil," there sounded a terrific crash which shook the building to its foundations, froze the blood in our veins, and cut short abruptly the petition which we had commenced. Dense dust mingled with debris and fragments of plaster dislodged from the ceiling, obscured our eyes, and acrid smell of burned sulphur spread through the place. Terrified and running like mad creatures, half blind with the cloud of dust, tumbling over each other under the shower of falling fragments, we anxiously sought the way out without finding it for a while. More fortunate or less paralyzed by fear than the others, one of the children reached the door and the rest rushed after him in terror. The vivid fear which we felt did not allow us to realize what had occurred. We thought that a mine had exploded, that the house had caved in, that the church had fallen down on to the school, everything occurred to us except a lightning stroke.
>
> Some good women who saw us running distractedly came at once to our assistance, gave us water, cleaned off the dusty perspiration which gave us the appearance of ghosts and bandaged temporarily those who had been hurt. A voice coming from among the crowd called our attention to a strange, blackish figure hanging on the railing of the bell tower. In fact, there, beneath the bell, enveloped in dense smoke, his head hanging over the wall lifelessly, lay the poor priest who had thought that he would be able to ward off the threatening danger by the imprudent tolling of the bell. Several men climbed up to help him and found him with his clothes on fire and with a terrible wound in his neck from which he died a few days later. The bolt had

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[14] W. Snow Harris, *On the nature of thunderstorms; and on the means of protecting buildings and shipping against the destructive effects of lightning* (London: John W. Parker, 1843), pp. v–vi.

[15] Cf. Snow Harris (ref. 14), p. 162; White (ref. 4, *supra*), vol. 1, pp. 367–368.

> passed through him, mutilating him horribly. In the school, the mistress lay senseless upon her dais, also struck by the lightning but without serious injuries.
>
> Little by little we took in what had happened. A bolt or flash of lightning had struck the tower, partly melting the bell and electrocuting the priest; afterwards, continuing its capricious path, it had entered the school through a window, had pierced the ceiling of the lower floor where we children were, shattering a great part of the ceiling, had passed behind the mistress, whom it deprived of sensibility, and, after destroying a picture of the Saviour hanging upon the wall, had disappeared through the floor, by a gap, a sort of mouse hole close to the wall.[16]

There is no way of telling when church bells were last rung for this purpose. Indeed, for all we know, they may still be used in a vain attempt to dissipate storms in isolated communities or backward countries. The refusal of the mind to change its ways can hardly be better illustrated by the slowness with which lightning rods were adapted to ecclesiastical structures in the 18th century. It is fantastic to think that in Spain a little more than a century after Franklin's demonstration of the electrical character of the lightning discharge, and the subsequent introduction of the lightning rods, church bells should have still been rung to the grim tune of death to the bell ringer in an attempt to counteract "the powers of the air."

Yet Spain was not alone in continuing this custom at so late a date. A late 19th century observer reported in the 1860's that in Upper Swabia the bells were still being rung in churches during thunder-storms to drive away the hail and prevent damage by lightning. In some of the churches, there were special bells that were used only for that purpose.[17] At the same period, bells were being rung in Constance during thunder-storms, and eager volunteers always were on hand to assist the sexton despite the fact that over the years many were struck dead.[18] A tourist in the Tyrolese Alps wrote in 1867 that "bell-ringing, as the companion of the thunder-storm is a permanent institution here. I could not make out whether it was supposed to have a physical influence on the electricity, or to have a propitiary effect in a religious sense, calculated to exempt the district from a calamity."[19] A commentary on the lack of progress is provided in an extract from an issue of the Torquay Directory (20th century) reading: "It transpires that in conformity with an old usage, the bells of Dawlish Church were rung during the recent thunderstorms, in the belief that the spirit of the bells would overcome the spirit of the lightning." [20] As late as 1906, an English writer on bells, J. J. Raven, was not ashamed of his belief that there was very likely a rational or natural explanation of the power of bells and that it might indeed be true that the bells can dispel lightning as so many had for so long believed.[21]

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[16] S. Ramón y Cajal, *Recollections of my life*, trans. by E. Horne Craigie (Philadelphia: American Philosophical Society [*Memoirs of the Amer. Philos. Soc.* **8**], 1937), pp. 21–23. In a recent biography of Ramón y Cajal, the author apparently could not bring herself to believe that anyone would have rung bells to prevent the effects of lightning; after describing the effects of the storm, she writes: "Just at that moment someone pointed to a black figure caught in the railing of the church belfry, its head hanging over the wall. It was the parish priest, who had tried to warn the people of the danger by tolling the church bell." [Dorothy F. Cannon, *Explorer of the human brain* (New York: Henry Schuman, 1949), pp. 7–8]. One would think that the thunder itself would provide a better (i. e., louder) "warning" than the bells; furthermore, what would the people be expected to do about the thunderstorm once they had been "warned"?

[17] A description of the Swabian bells written by Ernst Meier is given in Ernest Morris, *Legends o' the bells* (London: Sampson, Low, Marston & Co., n. d.), p. 20.

[18] *Ibid.*

[19] *Idem*, pp. 16–17; the quotation is given by Morris from *Blackwood's Magazine*, Nov. 1867, p. 543.

A man who knew about lightning and who was aware that bell-ringers were courting death by ringing the bells during a storm, would find his own feelings of anxiety aggravated rather than soothed by the mournful peal. A graphic description of such a man under those conditions is provided for us by the father of the novelist Fanny Burney in his journal of the tour which he made in Germany, the Netherlands, and the United Provinces in search for materials for the history of music. According to Burney,

> I had been told, that the people of Bavaria were, at least, 300 years behind the rest of Europe in philosophy, and useful knowledge. Nothing can cure them of the folly of ringing the bells whenever it thunders, or persuade them to put up conductors to their public buildings; though the lightning here is so mischievous, that last year, no less than thirteen churches were destroyed by it, in the electorate of Bavaria. The recollection of this, had not the effect of an opiate upon me; the bells in the town of Freising were jingling the whole night, to remind me of their fears, and the real danger I was in. I lay on the mattress, as far as I could from my sword, pistols, watch-chain, and everything that might serve as a conductor. I never was much frightened by lightning before, but I wished for one of Dr. Franklin's beds, suspended by silk cords in the middle of a large room.[22]

FRANKLIN'S TWO EXPERIMENTS ON THE ELECTRICAL NATURE OF THE LIGHTNING DISCHARGE: AND THE INTRODUCTION OF LIGHTNING RODS

An announcement of the lightning rod, containing directions for constructing one, was published by Franklin in "Poor Richard's Almanack" [23] for 1753 (this account is reproduced in facsimile as Fig. 1.) An advertisement of this issue of "Poor Richard" [24] appeared in *The*

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[20] Quoted in Morris (ref. 17, *supra*), p. 21. In J. R. Nichols, *Bells thro' the ages* (London: Chapman and Hall, 1928), p. 27, this extract is attributed to E. Morris in *The Bell News and Ringer's Record*, 23 Oct. 1915, p. 63.

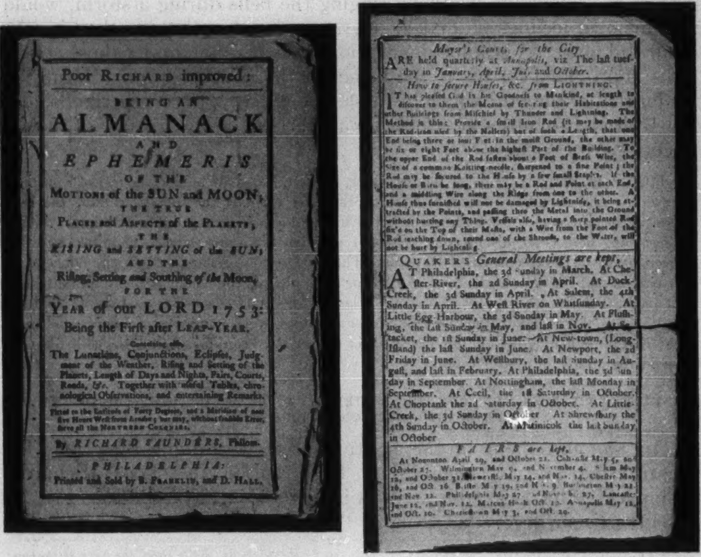
[21] J. J. Raven, *The bells of England* (London: Methuen & Co., 1906), p. 280.

[22] Charles Burney, *The present state of music in Germany, the Netherlands, and United Provinces* (London: T. Becket, J. Robson, G. Robinson, 1775), vol. 1, p. 183.

[23] The complete issue of "Poor Richard" for 1753 has been reproduced in facsimile in Frank Luther Mott and Chester E. Jorgenson, *Benjamin Franklin: representative selections, with introduction, bibliography, and notes* (New York, etc.: American Book Company, 1936), pp. 255–260; the description of the lightning rods appears on p. 257 of this reprint.

[24] Pedantic scholars often complain about the name "Poor Richard's Almanack," since the title page was of the form: "*Poor Richard improved: being an almanack and ephemeris . . . for the year of our Lord 1753: being the first after leap-year. . . . By Richard Saunders, Philom.* Philadelphia: Printed and sold by B. Franklin, and D. Hall"; the annual didn't have "Poor Richard's Almanack" on the title page. In the advertisement, however, Franklin called his own work "Poor Richard's Almanack" and surely his own taste in this matter may serve as our guide.

Pennsylvania Gazette for 19 October 1752, Numb. 1243—the same issue in which Franklin published an account of his famous kite experiment—and read: "In the Press, and speedily to be published, POOR RICHARD'S ALMANACK for the Year 1753." The lightning rod or lightning conductor was to be a long iron rod fastened vertically to the side of a house by iron staples, the upper end—joined to a foot of brass wire ending in a sharp point—rising six to eight feet above the highest part of the building, and the lower end being sunk from three to four feet in the moist earth or ground. In this description, the action of the rod was mentioned in a statement that a house protected with the new device "will not be damaged by Lightning, it being attracted by the Points, and passing thro the Metal into the Ground without hurting any Thing."



Poor RICHARD improved:
BEING AN
ALMANACK
AND
EPHEMERIS
OF THE
MOTIONS of the SUN and MOON;
THE TRUE
PLACES and ASPECTS of the PLANETS;
THE
RISING and SETTING of the SUN;
AND THE
Riſing, Setting and Southing of the Moon,
FOR THE
YEAR of our LORD 1753:
Being the Firſt after LEAP-YEAR.
Containing alſo,
The Lunations, Conjunctions, Eclipſes, Judgment of the Weather, Riſing and Setting of the Planets, Length of Days and Nights, Fairs, Courts, Roads, &c. Together with uſeful Tables, chronological Obſervations, and entertaining Remarks.
Fitted to the Latitude of Forty Degrees, and a Meridian of near five Hours Weſt from London; but may, without ſenſible Error, ſerve all the NORTHERN COLONIES.
By RICHARD SAUNDERS, Philom.
PHILADELPHIA:
Printed and Sold by B. FRANKLIN, and D. HALL.

Mayor's Courts for the City
ARE held quarterly at *Annapolis*, viz. The laſt Tueſday in *January*, *April*, *July*, and *October*.

How to ſecure Houſes, &c. from LIGHTNING.

IT has pleaſed God in his Goodneſs to Mankind, at length to diſcover to them the Means of ſecuring their Habitations and other Buildings from Miſchief by Thunder and Lightning. The Method is this: Provide a ſmall Iron Rod (it may be made of the Rod-iron uſed by the Nailers) but of ſuch a Length, that one End being three or four Feet in the moiſt Ground, the other may be ſix or eight Feet above the higheſt Part of the Building. To the upper End of the Rod faſten about a Foot of Braſs Wire, the Size of a common Knitting-needle, ſharpened to a fine Point; the Rod may be ſecured to the Houſe by a few ſmall Staples. If the Houſe or Barn be long, there may be a Rod and Point at each End, and a middling Wire along the Ridge from one to the other. A Houſe thus furniſhed will not be damaged by Lightning, it being attracted by the Points, and paſſing thro the Metal into the Ground without hurting any Thing. Veſſels alſo, having a ſharp pointed Rod fix'd on the Top of their Maſts, with a Wire from the Foot of the Rod reaching down, round one of the Shrouds, to the Water, will not be hurt by Lightning.

QUAKERS *General Meetings are kept*,

AT Philadelphia, the 3d Sunday in March. At Cheſter-River, the 2d Sunday in April. At Duck-Creek, the 3d Sunday in April. At Salem, the 4th Sunday in April. At Weſt River on Whitſunday. At Little Egg-Harbour, the 3d Sunday in May. At Fluſhing, the laſt Sunday in May, and laſt in Nov. At Setacket, the 1ſt Sunday in June. At New-town, (Long-Iſland) the laſt Sunday in June. At Newport, the 2d Friday in June. At Weſtbury, the laſt Sunday in Auguſt, and laſt in February. At Philadelphia, the 3d Sunday in September. At Nottingham, the laſt Monday in September. At Cecil, the 1ſt Saturday in October. At Choptank the 2d Saturday in October. At Little-Creek, the 3d Sunday in October. At Shrewſbury the 4th Sunday in October. At Matinicok the laſt Sunday in October

FAIRS are kept.

At Nottingham April 29, and October 21. Cohanſie May 5, and October 27. Wilmington May 9, and November 4. Salem May 12, and October 31. Newcaſtle May 14, and Nov. 14. Cheſter May 16, and Oct. 16. Briſtol May 19, and Nov. 9. Burlington May 21, and Nov. 12. Philadelphia May 27, and November 27. Lancaſter June 12, and Nov. 12. Marcus Hook Oct. 10. Annapolis May 12, and Oct. 10. Charleſtown May 3, and Oct. 29.

FIG. 1. Title page of "Poor Richard's Almanack" for 1753, and page [33] with the announcement of the lightning rod.

In a letter written from Philadelphia to Dr. John Mitchel, F. R. S., London on 29 April 1749, "Containing observations and suppositions, towards forming a new hypothesis, for explaining the several phenomena of thunder-gusts,"[25] Franklin advanced a number of observations tending to indicate the similarity if not the identity of lightning and electrical phenomena. If, as it appeared, lightning were nothing other than an electrical phenomenon, then the thunder-clouds must be electrified and their behaviour with regard to pointed conductors must be the same as had been observed by Franklin and his fellow-experimenters on other charged bodies in the laboratory.[26] Hence it seemed to Franklin, "As electrified clouds pass over a country, high hills and high trees, lofty towers, spires, masts of ships, chimneys, *&c.* as so many prominencies and points, draw the electrical fire, and the whole cloud discharges there." The conclusion was, "Dangerous, therefore, is it to take shelter under a tree, during a thunder-gust. It has been fatal to many, both men and beasts."

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[25] See *Benjamin Franklin's experiments* (ref. 1, *supra*), pp. 201–211. In Albert Henry Smyth, editor, *The writings of Benjamin Franklin*, vol. 3 (New York: The Macmillan Company, 1907), pp. 411–423, this letter is printed [erroneously] as if addressed to Peter Collinson; no date is given in the text, although in the table of contents the date is given as "1750 (?)."

In a paper entitled "Opinions and conjectures, concerning the properties and effects of the electrical matter, arising from experiments and observations, made at Philadelphia, 1749," which Franklin enclosed in a letter to Peter Collinson written from Philadelphia on 29 July 1750,[27] there was a description of experiments intended to provide a model of cloud discharge. A pair of large brass scales was hung from the cross-beam of a balance by insulating cords of silk. The beam was suspended from the ceiling by a pack-thread, so that the bottom of the scales was about one foot from the floor. The weight of the scales caused the pack-thread to untwist, producing a circular revolution of the scales at the ends of the beam. An iron punch was placed in a vertical position upon the floor, so that the scales would pass over it as they made their circular motion. If one of the brass scales were charged, the system would provide a small-scale mechanical model of an electrified cloud passing over a hill or a high building.

"Now if the fire of electricity and that of lightning be the same," wrote Franklin, "as I have endeavoured to shew at large, in a former paper, this . . . pasteboard tube [in another and similar experiment] and these scales may represent electrified clouds. If a tube of only ten feet long will strike and discharge its fire on the punch at two or three inches distance, an electrified cloud of perhaps 10,000 acres may strike and discharge on the earth at a proportionately greater distance." As the scales moved round, it was possible to observe a scale

> draw nigher to the floor, and dip more when it comes over the punch; and if that be placed at a proper distance, the scale will snap and discharge its fire into it. But if a needle be stuck on the

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[26] The action of points "in *drawing off* and *throwing off* the electrical fire" had been described by Franklin in his first communication to Peter Collinson on the subject of electricity, the letter dated 25 May 1747; see *Benjamin Franklin's experiments* (ref. 1, *supra*), p. 170. Thomas Hopkinson had found that a pointed, insulated, charged conductor will rapidly be discharged (or "throw off the electrical fire") while Franklin had found that a pointed conductor, placed with the point facing a charged, insulated conductor, will discharge the latter (or "draw off . . . the electrical fire")—slowly if the pointed conductor is insulated, rapidly if the pointed conductor is grounded.

[27] *Benjamin Franklin's experiments* (ref. 1, *supra*), pp. 212–236.

> end of the punch, its point upwards, the scale, instead of drawing nigh to the punch, and snapping, discharges its fire silently through the point, and rises higher from the punch. Nay, even if the needle be placed upon the floor near the punch, its point upward, the end of the punch, though so much higher than the needle, will not attract the scale and receive its fire, for the needle will get it and convey it away, before it comes nigh enough for the punch to act. . . .
>
> [Thus we may] see how electrified clouds passing over hills or high buildings at too great a height to strike, may be attracted lower until within their striking distance. And lastly, if a needle fixed on the punch with its point upright, or even on the floor below the punch, will draw the fire from the scale silently at a much greater than the striking distance, and so prevent its descending toward the punch; or if in its course it would have come nigh enough to strike, yet being first deprived of its fire it can not, and the punch is thereby secured from the stroke.

If all these things are actually so, concluded Franklin, "may not the knowledge of this power of points be of use to mankind, in preserving houses, churches, ships, *&c.* from the stroke of lightning, by directing us to fix on the highest parts of those edifices, upright rods of iron made sharp as a needle, and gilt to prevent rusting, and from the foot of those rods a wire down the outside of the building into the ground, or down round one of the shrouds of a ship and down her side until it reaches the water?" This statement contains the first description ever made by Franklin of the lightning rod.

Immediately following the above description of the way to protect buildings by lightning rods, Franklin returned to the question of their probable mode of action. "Would not these pointed rods probably draw the electrical fire silently out of a cloud before it came nigh enough to strike, and thereby secure us from that most sudden and terrible mischief?"

We may observe that Franklin offered no indication of the possibility that the lightning rods might act in another way as well, that they might safely conduct a stroke to the ground in addition to stealing the thunder from the clouds. His explanation of the probable action of lightning rods was based entirely on the property of pointed conductors (especially if grounded), in attracting electrical charge from a body at a considerable distance and, in the case of electrified clouds, silently causing them to discharge their electrical fire before there was any possibility of an actual stroke with its attendant destruction. The account published in "Poor Richard" (a little over a year after the letter to Collinson describing the lightning rods) is much less explicit as to the probable mode of action of the rods. Franklin merely said that the houses protected with lightning rods would not be damaged because the lightning, "being attracted by the points," would pass through "the metal into the ground without hurting anything." This statement may have been cautiously worded in order to admit of the two possible modes of action; more likely, Franklin took it for granted that the lightning rods would act by silently robbing the clouds of their thunder, and wrote a briefer account for public consumption than the earlier scientific report. Yet Franklin was soon to learn that the lightning

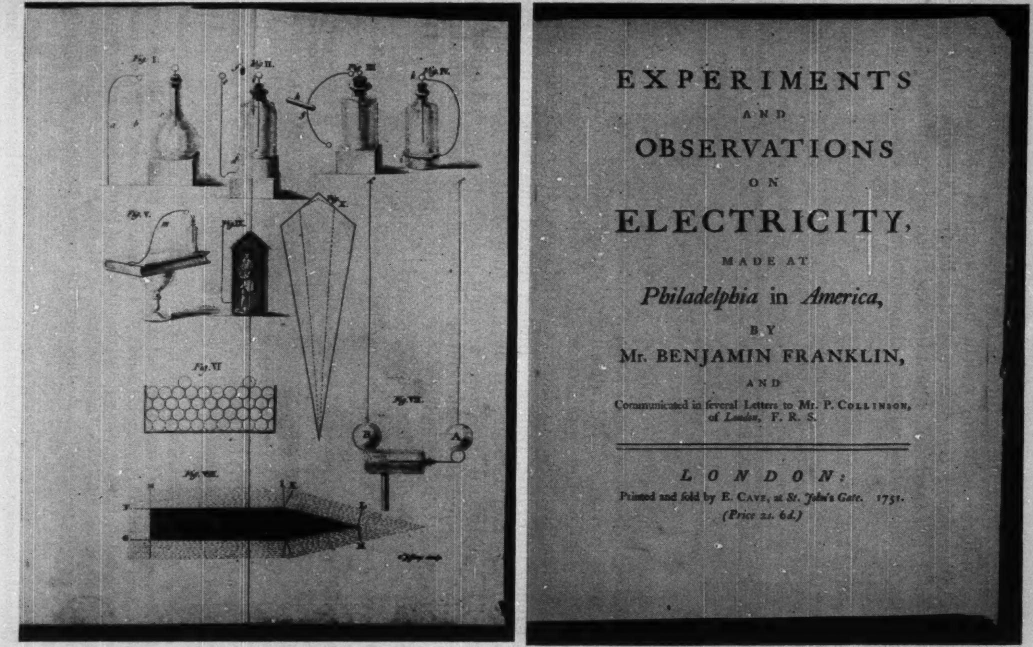
Fig. I
Fig. II
Fig. III
Fig. IV
Fig. V
Fig. IX
Fig. X
Fig. VI
Fig. VII
Fig. VIII

EXPERIMENTS
AND
OBSERVATIONS
ON
ELECTRICITY,
MADE AT
Philadelphia in *America*,
BY
Mr. BENJAMIN FRANKLIN,
AND
Communicated in ſeveral Letters to Mr. P. COLLINSON,
of *London*, F. R. S.

LONDON:
Printed and ſold by E. CAVE, at *St. John's Gate*. 1751.
(Price 2s. 6d.)

FIG. 2. Title page and frontispiece of the first book on electricity; "Fig. IX illustrates the sentry-box experiment devised by Franklin to show the electrification of clouds."

rods, in addition to their property of preventing a stroke, would also act so as to conduct the stroke itself safely into the ground.[27a]

If his ideas about the nature of the lightning discharge were to be accepted, and if the lightning rod he had invented was to be put into practice, an empirical test was needed. In the "Opinions and conjectures" of 1749, therefore, Franklin described an experiment having as its object to determine whether thunderclouds are electrified or not. His description follows:

> On the top of some high tower or steeple, place a kind of sentry-box [as in Fig. 2] big enough to contain a man and an electrical [i.e., insulating] stand. From the middle of the stand let an iron rod rise and pass bending out of the door, and then upright 20 or 30 feet, pointed very sharp at the end. If the electrical stand be kept clean and dry, a man standing on it when such clouds are passing low, might be electrified and afford sparks, the rod drawing fire to him from a cloud. If any danger to the man should be apprehended (though I think there would be none) let him stand on the floor of his box, and now and then bring near to the rod the loop of a wire that has one end fastened to the leads, he holding it by a wax handle; so the sparks, if the rod is electrified, will strike from the rod to the wire, and not affect him.[28]

This experiment of the sentry box was published in the first collection of material that made up Franklin's book on electricity. It issued from the press in April of 1751, although printing was evidently begun in 1750.[29] Soon after the appearance of Franklin's book in England, Franklin had begged Peter Collinson to send one of the first copies to the great French naturalist, Buffon. Buffon judged this book to have exceptional merit and arranged to have it translated by Jean François Dalibard [or d'Alibard].[30] Some account of the success of Franklin's book in France, and the performance of the sentry-box experiments, may be found in the following extract from a letter written by the Abbé Mazéas to Stephen Hales on 20 May 1752:

> The favour done me by the Royal Society obliging me to interest myself in whatsoever concerns their honour, I beg you will communicate the following account.
>
> The Philadelphian experiments, that Mr. Collinson, a member of the Royal Society, was so kind as to communicate to the public, having been universally admired in France, the King desired to see them performed. Wherefore the Duke D'Ayen offer'd his Majesty his country-house at St. Germain, where M. de Lor, master of experimental philosophy, should put those of

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[27a] [Note added in proof:] Dr. Schonland's article, which precedes mine in this symposium, discusses this same problem in a particularly illuminating way. See, especially, § 11, p. 384.

[28] *Benjamin Franklin's experiments* (ref. 1, *supra*), p. 222.

[29] See *Benjamin Franklin's experiments* (ref. 1, *supra*), pp. 82, 85, 87–88. Collinson wrote Franklin in April 1750 that his "electrical papers . . . are now on the press"; *The Gentleman's Magazine* (published by E. Cave, who was also the publisher of Franklin's book on electricity) for May 1750 noted that Franklin's "ingenious letters on this subject [electricity] will soon be published in a separate pamphlet"; in the December 1750 issue of *The Gentleman's Magazine,* Cave referred to "an account of some experiments made in America by Mr. B. Franklin (now in the press)."

[30] This is the statement made by Dalibard in the "avertissement" to his translation (Paris, 1752), p. 4. For an account of the editions of Franklin's book, see *Benjamin Franklin's experiments* (ref. 1, *supra*), pp. 141–148.

Philadelphia in execution. His Majesty saw them with great satisfaction, and greatly applauded Messieurs Franklin and Collinson. These applauses of his Majesty having excited in Messieurs de Buffon, D'Alibard, and De Lor, a desire of verifying the conjectures of Mr. Franklin, upon the analogy of thunder and electricity, they prepar'd themselves for makeing the experiments.

M. D'Alibard chose, for this purpose, a garden situated at Marly, where he placed upon an electrical body a pointed bar of iron, of 40 feet high. [See Fig. 3.] On the 10 of May, 20 minutes past 2 afternoon, a stormy cloud having passed over the place where the bar stood, those, that were appointed to observe it, drew near, and attracted from it sparks of fire, perceiving the same kind of commotions as in the common electrical experiments.

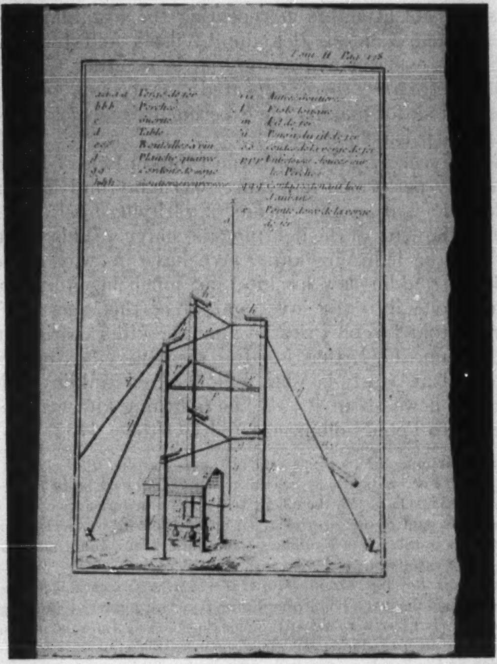

FIG. 3. The apparatus for the sentry-box experiment as performed at Marly-la-Ville by Dalibard; from the second edition of the latter's translation of Franklin's book on electricity.

M. de Lor, sensible of the good success of this experiment, resolved to repeat it at his house in the Estrapade at Paris. He raised a bar of iron 99 feet high, placed upon a cake of resin, two feet square, and 3 inches thick. On the 18 of May, between 4 and 5 in the afternoon, a stormy cloud having passed over the bar, where it remain'd half an hour, he drew sparks from the bar. These sparks were like those of a gun, when, in the electrical experiments, the globe is only rubb'd by the cushion, and they produced the same noise, the same fire, and the same crackling. They drew the strongest sparks at the distance of 9 lines, while the rain, mingled

> with a little hail, fell from the cloud, without either thunder or lightning; this cloud being, according to all appearance, only the consequence of a storm, which happen'd elsewhere.
>
> From this experiment we conjectur'd, that a bar of iron, placed in a high situation upon an electrical body, might attract the storm, and deprive the cloud of all its thunder. I do not doubt but the Royal Society has directed some of its members to pursue these experiments, and to push this analogy yet further.[31]

On 21 December 1752 William Watson read to the Royal Society an account of successful attempts at repeating the Franklin experiment in England: by John Canton, Benjamin Wilson, and John Bevis.[32] So popular did this experiment become that in the July 1753 issue of *The Gentleman's Magazine*, there appeared an account of a "Machine, easily constructed, for making the experiment by which Franklin's new theory of thunder is demonstrated."

During the year 1752 in which the Franklin sentry-box experiment was successfully performed in France, Germany and England, Benjamin Franklin devised another means of verifying his hypothesis about the electrical character of the lightning discharge. This was the famous experiment of the lightning kite. (We have no way of determining exactly when Franklin flew his kite and much ingenuity in historical research has gone into the investigation of this question.[33] Fifteen years later, he told Joseph Priestley that the kite experiment had been performed in June 1752, that is, after the sentry-box experiment had been performed at Marly-la-Ville, but before Franklin could possibly have heard the news about it.[34]) The lightning kite was described by him in a letter to Peter Collinson dated 1 October 1752; this letter was

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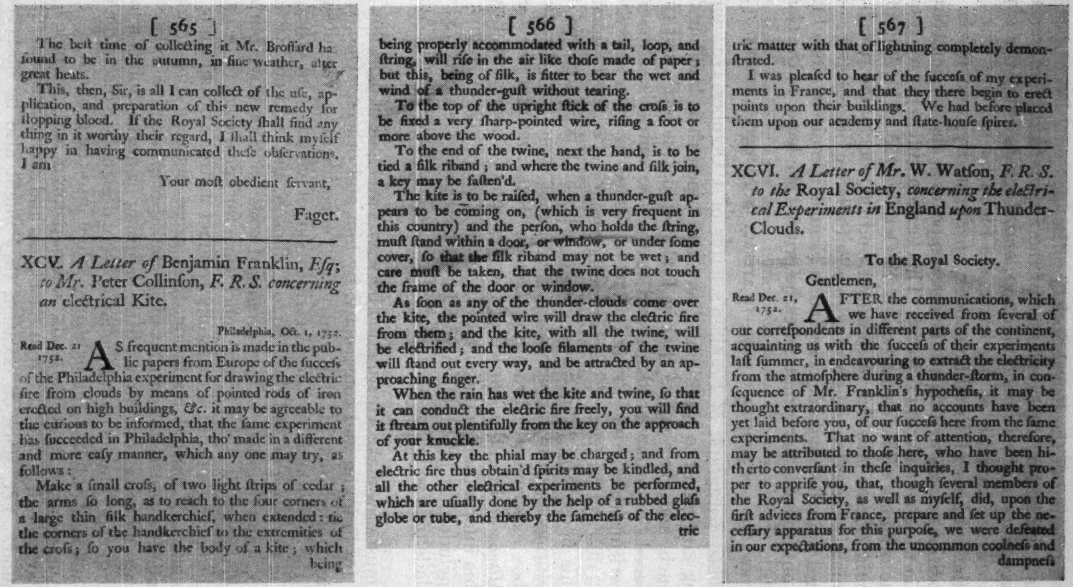
[31] From the contemporaneous translation by James Parsons, *Phil. Trans. Roy. Soc.* **47**: 534–535, 1751–1752. Further lightning experiments in France may be found described in the same issue, pp. 536–552. On p. 559, there is an account of a performance of this experiment in Berlin. A detailed account of the experiment set up by Dalibard was included by him in the second edition of his translation of Franklin's book (Paris, 1756), and it may also be found in *Benjamin Franklin's experiments* (ref. 1, *supra*), pp. 257–262.

[32] See *Phil. Trans. Roy. Soc.* **47**: 567–570, 1751–1752: ". . . several members of the Royal Society . . . did, upon the first advices from France, prepare and set up the necessary apparatus for this purpose, [but] we were defeated in our expectations, from the uncommon coolness and dampness of the air here, during the whole summer." There had been but one thunderstorm in London and it had been accompanied by rain which wet the apparatus. Canton, Wilson, and Bevis had performed the experiment away from London, but the effects they had obtained were "trifling" when compared to those reported from Paris and Berlin; yet, since "they were made by persons worthy of credit, they tend to establish the authenticity of those transmitted from our correspondents." This account is reprinted in *Benjamin Franklin's experiments* (ref. 1, *supra*), pp. 262–264

[33] An account of research on this question may be found in Marcus W. Jernegan, "Benjamin Franklin's electrical kite and lightning rod," *New England Quarterly* 1: 180–196, 1928. (This article supersedes the earlier ones by Abbott Lawrence Rotch and Alexander McAdie.) See also Carl Van Doren, *Benjamin Franklin* (New York: The Viking Press, 1938), pp. 164–170. Some new evidence on this subject will be found in I. B. Cohen, "Benjamin Franklin's two lightning experiments and the introduction of the lightning rod," *Proceedings of the American Philosophical Society* [in press].

[34] Franklin knew of the experiment at Marly-la-Ville in August 1752.



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The beſt time of collecting it Mr. Broſſard has found to be in the autumn, in fine weather, after great heats.

This, then, Sir, is all I can collect of the uſe, application, and preparation of this new remedy for ſtopping blood. If the Royal Society ſhall find any thing in it worthy their regard, I ſhall think myſelf happy in having communicated theſe obſervations. I am

Your moſt obedient ſervant,

Faget.

XCV. *A Letter of* Benjamin Franklin, *Eſq; to Mr.* Peter Collinſon, *F. R. S. concerning an* electrical Kite.

Philadelphia, Oct. 1, 1752.

Read Dec. 21 1752.

AS frequent mention is made in the public papers from Europe of the ſucceſs of the Philadelphia experiment for drawing the electric fire from clouds by means of pointed rods of iron erected on high buildings, *&c.* it may be agreeable to the curious to be informed, that the ſame experiment has ſucceeded in Philadelphia, tho' made in a different and more eaſy manner, which any one may try, as follows:

Make a ſmall croſs, of two light ſtrips of cedar; the arms ſo long, as to reach to the four corners of a large thin ſilk handkerchief, when extended: tie the corners of the handkerchief to the extremities of the croſs; ſo you have the body of a kite; which

being

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being properly accommodated with a tail, loop, and ſtring, will riſe in the air like thoſe made of paper; but this, being of ſilk, is fitter to bear the wet and wind of a thunder-guſt without tearing.

To the top of the upright ſtick of the croſs is to be fixed a very ſharp-pointed wire, riſing a foot or more above the wood.

To the end of the twine, next the hand, is to be tied a ſilk riband; and where the twine and ſilk join, a key may be faſten'd.

The kite is to be raiſed, when a thunder-guſt appears to be coming on, (which is very frequent in this country) and the perſon, who holds the ſtring, muſt ſtand within a door, or window, or under ſome cover, ſo that the ſilk riband may not be wet; and care muſt be taken, that the twine does not touch the frame of the door or window.

As ſoon as any of the thunder-clouds come over the kite, the pointed wire will draw the electric fire from them; and the kite, with all the twine, will be electrified; and the looſe filaments of the twine will ſtand out every way, and be attracted by an approaching finger.

When the rain has wet the kite and twine, ſo that it can conduct the electric fire freely, you will find it ſtream out plentifully from the key on the approach of your knuckle.

At this key the phial may be charged; and from electric fire thus obtain'd ſpirits may be kindled, and all the other electrical experiments be performed, which are uſually done by the help of a rubbed glaſs globe or tube, and thereby the ſameneſs of the elec-

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tric matter with that of lightning completely demonſtrated.

I was pleaſed to hear of the ſucceſs of my experiments in France, and that they there begin to erect points upon their buildings. We had before placed them upon our academy and ſtate-houſe ſpires.

XCVI. *A Letter of Mr.* W. Watſon, *F. R. S. to the* Royal Society, *concerning the electrical Experiments in* England *upon* Thunder-Clouds.

To the Royal Society.

Gentlemen,

Read Dec. 21, 1752.

AFTER the communications, which we have received from ſeveral of our correſpondents in different parts of the continent, acquainting us with the ſucceſs of their experiments laſt ſummer, in endeavouring to extract the electricity from the atmoſphere during a thunder-ſtorm, in conſequence of Mr. Franklin's hypotheſis, it may be thought extraordinary, that no accounts have been yet laid before you, of our ſucceſs here from the ſame experiments. That no want of attention, therefore, may be attributed to thoſe here, who have been hitherto converſant in theſe inquiries, I thought proper to appriſe you, that, though ſeveral members of the Royal Society, as well as myſelf, did, upon the firſt advices from France, prepare and ſet up the neceſſary apparatus for this purpoſe, we were defeated in our expectations, from the uncommon coolneſs and

dampneſs

FIG. 4. Franklin's letter to Collinson (describing the kite experiment and indicating the erection of lightning rods in Philadelphia), as it appeared in the *Philosophical Transactions* of the Royal Society of London.

read at a meeting of the Royal Society of London on 2 December 1752 and was published in the same issue of the *Philosophical Transactions*[35] as the accounts of the French, German, and English sentry-box experiments. (For a facsimile of this letter, see Fig. 4.)

In the editions of Franklin's book on electricity, and in the collected editions of his writings, this letter appears in the version that appeared in the *Pennsylvania Gazette*. This version differs in two respects from the original. The date given is 19 October 1752, the date of the issue of the *Gazette* in which it appeared, and the concluding paragraph, mentioning the erection of lightning rods in Philadelphia before Franklin had heard that they had been erected in France, is omitted since Franklin had omitted this paragraph when he printed the letter in the *Gazette*.

THE ACTION OF LIGHTNING RODS—TO ATTRACT OR PREVENT A STROKE?

The last paragraph of Franklin's letter of 1 October 1752 on the lightning kite refers to the "points" erected "upon their buildings" by the French, and gives notice that in Philadelphia "points" had earlier been placed "upon our academy and statehouse spires." Three days before writing this letter, Franklin had published in the *Pennsylvania Gazette* a description from Brussels of a lightning rod erected "upon the top of his house" by "the Sieur Torre," who had been able to draw sparks during a storm, apparently repeating in some form Franklin's sentry-box experiment. From the *London Magazine* and the *Gentlemen's Magazine* Franklin learned of the erection of "points" in France. Since this information had come to hand by the middle of August, we may conclude that Franklin implied in his letter of 1 October 1752 that the Philadelphia rods had been erected before late July or early August 1752.

We must now make a distinction between two kinds of lightning rods devised by Franklin and constructed by him and others. One, which was ungrounded (as in the sentry-box experiment), was designed to test the hypothesis of the electrification of clouds; the other, described in the letter of 29 July 1750 to Collinson, and in "Poor Richard" for 1753, was grounded. Once grounded rods for protective purposes had been erected, it did not take much time for knowledge to be gained that lightning rods could successfully conduct a stroke of lightning into the ground. A natural confusion then arose between the action of ungrounded or test-rods and that of grounded or protective rods. The former was a device to attract a little lightning from the clouds in order to perform experiments on it; the latter were designed to discharge electrified clouds or conduct the lightning safely into the ground.

Let us suppose that the rods, being pointed and grounded, did usually attract electrical fire from the clouds and silently conduct it into the ground. Yet, since on occasion they might also be observed to conduct a stroke of lightning into the ground, the conclusion seems perfectly legitimate that the rod which had attracted the fire silently had now invited a stroke of lightning which otherwise might not have come near the building at all. Thus many individuals were opposed to the use of lightning rods because they believed that the rod invited a lightning stroke which might otherwise, with luck, have been avoided entirely.[36]

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[35] *Phil. Trans. Roy. Soc.* **47**: 565–567, 1751–1752.

One of the famous controversies about the nature of lightning rods in the 18th century centered on the issue of whether they should end in sharp points (as Franklin had suggested) or round spherical knobs.[37] A considerable part of this controversy hinged on the question of whether they would attract a lightning stroke more readily in the one case than in the other and, hence, increase the possibility of danger in case the lightning rod would not safely conduct the stroke into the ground. The fear that lightning rods might produce an unnecessary risk has been described as follows:

> Benjamin Wilson . . . [the chief advocate of "blunt" rods or rods ending in metal knobs] was so suspicious of the attractive power of the rod that he went so far as to advise in 1764 that the rod should not extend above the building at all but should end in a blunt point or knob below the roof. He was, however, outdone by others, who considered that the attractive action of the rod could be reversed, and the lightning-stroke repelled, by fitting the tip of the conductor with insulating glass balls. Such balls were fitted to the vane-rod on the steeple of Christ Church, Doncaster. The result was hardly satisfactory, for the steeple was demolished by a lightning-flash not long after.[38]

Wilson, a Fellow of the Royal Society, believed that pointed conductors may promote "the very mischief we mean to prevent" since they act by "soliciting the lightning and . . . also frequently occasioning a discharge when it might otherwise not have happened."

Actually, Wilson was wholly wrong in assuming the attractive influence of a lightning rod to be in any way harmful; "experience over two centuries has shown that by this influence the rod gives complete protection to a building within a certain radius." [39] Yet he was right in his assumption that blunt conductors work just as well as pointed ones, although he did not advance this idea for the proper reason. In experiments performed on the scale of the laboratory, in which the scale pans of a balance or tufts of cotton serve to represent an electrified cloud, the difference in action between a near-by pointed conductor and a blunt-ended one is marked. In terms of the actual dimensions of a thundercloud, compared to a lightning conductor, there is no difference in action between the two kinds of tip—blunt or pointed. The controversy dissolves in the change of scale from the laboratory to the field.

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[36] In 1843, Snow Harris believed that the fear of unnecessarily inviting a lightning stroke was the chief cause of prejudice against lightning rods; pages 176–186 of his book (ref. 14, *supra*) are devoted to this question. We are told, pp. 176–177, that "the Govenor-general and Council of the Honourable the East India Company were led to order the lightning rods to be removed from their powder magazines and other public buildings, having in the year 1838 come to the conclusion, from certain representations of their scientific officers, that lightning rods were attended by more danger than advantage; in the teeth of which conclusion, a magazine at Dum Dum, and a corning-house at Mazagon, not having lightning rods, were struck by lightning and blown up." Harris also quoted, p. 177, from a book published in 1829, "Science has every cause to dread the thunder rods of Franklin: they attract destruction, and houses are safer without any of them."

[37] For the nature of this controversy see *Benjamin Franklin's experiments* (ref. 1, *supra*), Schonland (ref. 11, *supra*), and Weld (ref. 13, *supra*).

[38] Schonland (ref. 11, *supra*), p. 31.

[39] *Ibid.*

In a letter to Dalibard dated Philadelphia 29 June 1755, and read at a meeting of the Royal Society of London on 18 December 1755, Franklin wrote that he had been "but partly understood" in the matter of "points in drawing the electrical matter from clouds, and thereby securing buildings."

> I have mentioned it in several of my letters, and except once, always in the alternative, viz. that pointed rods erected on buildings, and communicating with the moist earth, would either prevent a stroke, or, if not prevent it, would conduct it, so as that the building should suffer no damage. Yet whenever my opinion is examined in Europe, nothing is considered but the probability of these rods preventing a stroke of explosion, which is only a part of the use I propose for them; and the other part, their conducting a stroke, which they may happen not to prevent, seems to be totally forgotten, though of equal importance and advantage.[40]

This letter was published in Franklin's book on electricity and in a note added to the fifth edition (1774), Franklin stated:

> Notwithstanding this complaint of the author's, repeated in four editions of his papers, he continues to be misunderstood and misrepresented in this particular, as if he considered it as the sole use of pointed rods, that they might draw off the lightning from the clouds and, prevent a stroke; and the very instances adduced by him to show that the rods had protected houses, by conducting the lightning when there was a stroke, proved by its having melted the points, are said to be instances of conductors being UNSUCCESSFUL,—in a pamphlet entitled Observations Upon Lightning, &c., just published, 1773.[41]

Twenty years after the invention of lightning rods, Franklin was able to report their progress in a letter which he wrote to Professor John Winthrop on 25 July 1773 from London: "Conductors begin to be used here. Many country seats are furnished with them, some churches, the powder magazine at Purfleet, the queen's house in the park, . . ."[42] The tone of this letter may be compared to that of his letter to his fellow-experimenter Kinnersley eleven years earlier, in 1762: "You seem to think highly of this discovery, as do many others on our side of the water. Here [in England] it is very little regarded; so little, that, though it is now seven or eight years since it was made public, I have not heard of a single house as yet attempted to be secured by it."[43] In 1772, he wrote a report, presumably to H. B. de Saussure, the Swiss naturalist, which described the progress in the use of lightning rods:

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[40] *Benjamin Franklin's experiments* (ref. 1, *supra*), pp. 307 ff.

[41] *Idem*, p. 308 n.

[42] Smyth, Writings (ref. 25, *supra*), vol. 6, p. 107. The first lightning rod for protective purposes to be erected in England appears to have been the one on Watson's house in 1762.

[43] *Idem*, vol. 1, p. 103.

> Pointed conductors to secure buildings from Lightning have now been in use near 20 Ye[ar]s in America, and are there become so common, that Numbers of them appear on private Houses in every Street of the principal Towns, besides those on Churches, public Buildings, Magazines of Powder, and Gentlemen's Seats in the Country. Thunder Storms are much more frequent there than in Europe, and hitherto there has been no Instance of a House so guarded being damaged by Lightning; for wherever it has broke over any of them the Point has always receiv'd it, & the Conductor has convey'd it safely into the Earth, of which we have now 5 authentick Instances. Here in England, the Practice has made a slower Progress, Damage by Lightning being less frequent, & People of course less apprehensive of Danger from it; yet besides St. Paul's Church, St. James Church, the Queen's Palace, & Blenheim's House, a Number of private Gentlemen's Seats round the Town are now provided with Conductors, and the Ships bound to the East & W. Indies & the Coast of Guinea begin to supply themselves with Chains for that purpose made by Mr. Nairne, especially since the Return of Messrs Banks & Solander, who relate that their Ship was as they think saved by one of those Chains from Damage when a Dutch Man of War lying near them in the Road of Batavia was almost demolished by the Lightning.[44]

In September 1767, Franklin wrote a description "of lightning, and the method (now used in America) of securing buildings and persons from its mischievous effects."

> An iron rod being placed on the outside of a building from the highest part continued down into the moist earth, in any direction strait or crooked, following the form of the roof or other parts of the building, will receive the lightning at its upper end, attracting it so as to prevent it's striking any other part; and, affording it a good conveyance into the earth, will prevent its damaging any part of the building.
>
> A small quantity of metal is found able to conduct a great quantity of this fluid. A wire no bigger than a goose quill, has been known to conduct (with safety to the building as far as the wire was continued) a quantity of lightning that did prodigious damage both above and below it; and probably larger rods are not necessary, though it is common in America, to make them of half an inch, some of three quarters, or an inch diameter.
>
> The rod may be fastened to the wall, chimney, *&c.* with staples of iron. . . . The lightning will not leave the rod (a good conductor) to pass into the wall (a bad conductor), through these staples. . . . It would rather, if any were in the wall, pass out of it into the rod to get more readily by that conductor into the earth.
>
> If the building be very large and extensive, two or more rods may be placed at different parts, for greater security.
>
> Small ragged parts of clouds suspended in the air between the great body of clouds and the earth (like leaf gold in electrical experiments), often serve as partial conductors for the lightning, which proceeds from one of them to another, and by their help comes within the striking

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[44] *Lightning rods* (ref. 6, *supra*). De Saussure had erected a rod on his house in Geneva in 1771, which had caused so much anxiety to his neighbors that he feared a riot. To quell their fears he published a pamphlet that was later "translated into Italian and reissued at Venice," according to Douglas W. Freshfield, *The life of Horace Benedict de Saussure* (London: Edward Arnold, 1920), p. 130. (Cf. *infra*, above note 62.) In Freshfield's list of de Saussure's writings, this pamphlet is listed as: "Exposition abrégée de l'Utilité des Conducteurs Electriques. 4to, pp. 9. Genève, 1771." An extract from this pamphlet is published in Richard Anderson, *Lightning conductors: their history, nature, and mode of application* (London: E. & F. N. Spon, 1880), pp. 43–44. De Saussure wrote to Franklin from Naples on 23 February 1773 that the pamphlet had been successful in allaying the fears of his neighbors and that he had "had the pleasure of watching the electricity from the clouds during the whole course of the last summer. Several persons even followed this example, and raised conductors either upon their houses or before them. M. de Voltaire was one of the first. He does the same justice to your theory that he did to that of the immortal Newton." Quoted from Smyth, Writings (ref. 25, *supra*), vol. 1, p. 104.

> distance to the earth or a building. It therefore strikes through those conductors a building that would otherwise be out of the striking distance.
>
> Long sharp points communicating with the earth, and presented to such parts of clouds, drawing silently from them the fluid they are charged with, they are then attracted to the cloud, and may leave the distance so great as to be beyond the reach of striking.
>
> It is therefore that we elevate the upper end of the rod six or eight feet above the highest part of the building, tapering it gradually to a fine sharp point, which is gilt to prevent its rusting.
>
> Thus the pointed rod either prevents a stroke from the cloud, or, if a stroke is made, conducts it to the earth with safety to the building.
>
> The lower end of the rod should enter the earth so deep as to come at the moist part, perhaps two or three feet; and if bent when under the surface so as to go in a horizontal line six or eight feet from the wall, and then bent again downwards three or four feet, it will prevent damage to any of the stones of the foundation.
>
> A person apprehensive of danger from lightning, happening during the time of thunder to be in a house not so secured, will do well to avoid sitting near the chimney, near a looking-glass, or any gilt pictures or wainscot; the safest place is in the middle of the room, (so it be not under a metal lustre suspended by a chain) sitting in one chair and laying the feet up in another. It is still safer to bring two or three mattrasses or beds into the middle of the room, and folding them up double place the chair upon them; for they not being so good conductors as the walls, the lightning will not chuse an interrupted course through the air of the room and the bedding, when it can go through a continued better conductor the wall. But where it can be had, a hammock or swinging bed, suspended by silk cords equally distant from the walls on every side, and from the ceiling and floor above and below, affords the safest situation a person can have in any room whatever; and what indeed may be deemed quite free from danger of any stroke by lightning.[45]

The final sentence above contains the account of the lightning bed to which Dr. Burney referred in his story about the lightning storm in Bavaria.

I have referred above to the fact that the Abbé Nollet did not endorse the use of lightning rods and have mentioned Franklin's annoyance at Nollet's rejection of the new invention despite his recognition of the nature of the path of lightning. Nollet's attitude was part of his general antipathy to Franklin, whose work had achieved so great a fame and popularity in France that his own position as the leader of electrical thought had been greatly damaged. Furthermore, Franklin's unitary theory of electrical action in terms of the simple movement of a single electrical fluid constituted a flat contradiction of everything Nollet had been teaching on electricity.

In Nollet's report on lightning and lightning rods, published in 1764, and in which he had declared that the rods placed outside of a building are useless and dangerous, he had said, "Our curiosity can perhaps be applauded for the researches which it has caused us to make on the nature of thunder and on the mechanism of its principal effects," but how much more worth while it would be if "we could find some means to protect ourselves from them." [46] Such a discovery is supposed to have been made, he went on,

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[45] *Benjamin Franklin's experiments* (ref. 1, *supra*), pp. 388 ff.

[46] Published in 1764 (ref. 4, *supra*).

> but unfortunately twelve years of proofs and a little reflection teaches us that we can not count on the promises which have been made to us. I have said a long time ago and with regret that all these points of iron which one shoots up in the air, whether as electroscopes, whether as preservatives, can well inform us that it is thundering or that it is about to thunder; but if it is a question of the good that they can do us, I believe that they are more suitable to attract the fire of thunder to us than to preserve us from it: this is sufficiently proved by the death of the unfortunate M. Richmann, whatever way he had used the iron rod of his fatal experiment; I persist in saying that the project of emptying a thunder cloud of the fire with which it is charged is not that of a physicist.

Richmann's electrocution in 1753[47] seemed to provide an empirical basis for those who feared the lightning rod. Yet Nollet was plainly mistaken in introducing this event into the discussion, since Richmann had been killed while using an *ungrounded* rod for test purposes and not a *grounded* rod such as would be used to protect a house. Nollet's introduction of the phrase "whatever way he had used the iron rod in his fatal experiment" (*de quelque façon qu'il ait employé la barre de fer de sa fatale expérience*) suggests a willful confusion rather than a naïve lack of understanding of the role of grounding in experiments with conductors.

The above perversion of the facts (or possible—though doubtful—misunderstanding of them) occurred also in Nollet's book of "Letters on Electricity," published in 1753, largely devoted to replying to and attacking Franklin's book on electricity.[48] Although Nollet stated that the letters were intended "less as a criticism of M. Franklin's doctrine than as a defense of my own," the text itself indicates the contrary to be more nearly the case. Nollet had been induced to

> examine with care what may truly be concluded from the experiments proposed by M. Franklin and since carried into execution in France and elsewhere, in relation to the electricity of the clouds during a storm. . . . [By weighing every circumstance] and comparing the greatness of the effects, which have been had in view, with the more than apparent insufficiency of the means, which have been employed to produce them, I believe I have seen clearly that considering the electrification of pointed bodies as a proof of lessening the matter of thunder, is abusing a real discovery to flatter ourselves with a vain hope; and it is in part to dissipate this error, if it yet subsists, that determined me to print, in these letters, some reflections which I had made at first only for myself, and a few persons, to whom I was desirous of communicating my opinion.

In the first of the nine letters comprising the book, Nollet wrote that "from the phenomenon of Marly-la-Ville, and those discoveries which have been made since and to which it gave rise have been drawn the two following consequencies: one, that the matter of thunder and that of electricity are one and the same; the other, that by the means of pointed iron rods, one might, without noise or harm, draw off all the fulminating matter from a storm-cloud." In Watson's review of this book, in the *Philosophical Transactions* of the Royal Society, he noted at this point: "But our author has shown, that bodies being pointed are not absolutely necessary; and is desirous, we should not too hastily believe, that mischiefs arising from thunder may be averted by the apparatus proposed. He thinks the means vastly too small for the greatness of the cause."

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[47] Georg Wilhelm Richmann was electrocuted in St. Petersburg while performing an experiment in order to determine the "amount" of electricity in a lightning discharge by the use of an ungrounded test-rod. This was the first fatal accident to occur during an electrical experiment and it was widely discussed throughout the world. For a list of contemporary accounts of Richmann's death, see P. Fleury Mottelay, ***Bibliographical history of electricity and magnetism*** (London: Charles Griffin & Co., 1922), pp. 204–205.

[48] A second edition—*Lettres sur l'électricité* (Paris: H. L. Guérin & L. F. Delatour, 1754)—contained a second group of letters, "Dans lesquelles on soutient le principe des effluences & affluences simultanées, contre la doctrine de M. Franklin, & contre les nouvelles prétentions de ses partisans." The translations from this book are largely based on those made by Watson for his review in *Phil. Trans. Roy. Soc.* **48**: 201–213, 1753.

The seventh letter of the book dealt with "the analogy between lightning and electricity." Nollet stated emphatically that he could not believe in the efficacy of lightning rods: "First, because I see too great a disproportion between the effect and the cause; secondly, because the principle, which is given us to support this opinion, does not seem to me sufficiently established." Nollet could not believe that the fulminating matter contained in a cloud capable of covering a great city could be drawn off in a few minutes by a pointed bar as thick as a finger, and ridiculed the credulity of any one who gave serious consideration to lightning rods. Was not this supposed invention to be compared to placing tiny tubes in torrents to prevent a flood? If all that was needed to protect us from the thunder-bolts was some pointed bodies placed upon the tops of buildings, would not the spires and crosses (of which the arms usually are pointed at the ends) at the tops of our steeples have been sufficient to provide the protection we desire? Yet churches have never been exempted from the mischiefs of thunder. Thus, as Watson noted, the Abbé Nollet "despairs of our weak efforts ever being able to disarm the heavens." As Franklin pointed out in a great many of his pieces on the effects of lightning, the answer to Nollet lay in the fact that the spires, crosses and other metal objects on steeples were not grounded by a heavy wire, and might be compared to a test-rod but not a protective one. Indeed, it was this very lack of grounding which made them more dangerous than an ordinary building without a steeple having a mass of metal at the top. For this reason the Royal Society's committee had recommended the grounding of the cross atop St. Paul's.

Nollet's objections seem to be grounded in scientific concerns. Yet one has the feeling, in reading the whole literature of controversy written by Nollet against Franklin's invention, that what really rankled was the wound to his pride in the degree to which Franklin's ideas had superseded his own,[49] and that he objected first and then sought for a scientific basis for rejecting the lightning rod. That his influence considerably retarded the adoption of lightning rods, there can be little doubt.

A POPE AND A PRIEST ATTEMPT TO INTRODUCE LIGHTNING RODS

All too often we tend to think of churches as vested interests opposing all forms of progress. In the case of lightning rods this is not entirely the case, although it did take some years for Protestants and Catholics alike to begin to erect lightning rods on their churches. Even though the ringing of church bells during lightning storms continued in Catholic countries long after the invention of the lightning rod, it was by no means the case that the Church as an institution was opposed to the new invention. For example, as we saw in an earlier section, it was only fourteen years after the demonstration that lightning was electrical that lightning conductors were placed upon St. Mark's in Venice. Furthermore, in at least two instances that I have found in the 18th century, Church officials tried to erect lightning rods but were frustrated by the antagonism engendered by popular superstition. Despite the enlightened attitude of these Church officials, ignorance prevailed, and in both of these instances the lightning rods already erected were dismantled or destroyed.

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[49] For an account of the Franklin-Nollet controversy, see *Benjamin Franklin's experiments* (ref. 1, *supra*), pp. 74–75, 108, 113–118.

The first of these was a lightning rod erected on 15 June 1754, by Procopius Diviš [Diviss, or Diwish], an amateur "electrician," in the town of Přímětice [Prenditz, or Brenditz] in Moravia. Diviš was a monk of the Premonstratensian Order. His lightning rod—or "machina meteorologica," as he called it—was not like Franklin's and was composed of a pole topped by an iron rod which supported twelve branches of iron curving up like the branches of a tree each of which terminated in an iron box filled with iron ore, closed with a boxwood cover containing 27 sharp iron points which plunged at their base into the ore. The machine was grounded by metal chains.[50]

The claim is usually made that this form of lightning rod was an wholly independent invention on the part of Diviš.[51] There is certainly no ground for doubting that this peculiar form of lightning rod was invented by Diviš; at least no one has ever found a reference to any lightning rod like it prior to 1754. Some legitimate doubt exists, however, as to whether Diviš invented his rod without ever having heard of the work of Franklin. It is difficult to suppose that by 1754 Diviš had not heard of Franklin's experiments to prove the electrical character of the lightning discharge, which were described in many Continental publications—books, general magazines, and scientific journals. He undoubtedly knew of the sentry-box experiment, since he was acquainted with the tragic death of Richmann who had been killed by a lightning stroke in St. Petersburg in 1753 in a variation of this experiment.

In any event, Diviš's rod remained standing for six years, until March 1760 when the people of the village tore it down. Apparently the initial cause of hostility was a great drought which the peasants attributed to the malign influence of the rod. On the other hand, it has also been stated that Diviš's enemies, "jealous of this success at the Court of Vienna," excited "the peasants of the locality against him . . . under the pretext that his lightning rod was the cause of the great drought." [52] Whether the peasants' reaction against the rod was spontaneous, or whether the fires of their hatred had been fanned by the enemies of Diviš, the fact remains that the peasants were hostile to the new instrument, that in the end their superstition proved to be sufficiently powerful to effect the destruction of the rod.

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[50] Cf. Mottelay (ref. 47, *supra*), p. 209; also Brother Potamian and James J. Walsh, *Makers of electricity* (New York: Fordham University Press, 1909), pp. 108–114.

[51] The work of Diviš has been often discussed. A survey of the literature concerning him and his work may be found in Karel Hujer, "Procopius Diviš, the European Franklin," *Isis* **43** (1952, in press).

A somewhat similar episode occurred in Italy, and is rendered all the more interesting in that the Pope himself interceded in favor of the new invention. Franklin's ideas had been publicized in Italy by Father Giovanni Baptista Beccaria; Franklin was partly responsible for having his famous book, *Artificial and Natural Electricity*, translated into English.[53] As a Franklinist, Beccaria attacked the Abbé Nollet. He repeated many of Franklin's experiments—in particular, that of the lightning kite—and became one of the foremost authorities on the subject of atmospheric electricity. Not quite so well known, but of great interest, are Beccaria's experiments on the electrolysis of metallic compounds, about a half a century before the famous experiments of a similar kind by Davy. Performed long before Volta's invention of the electric battery, these interesting electrolysis experiments of Beccaria never attracted in their own lifetime the attention they deserved and even today are largely unknown to chemists.

An important source of information concerning Beccaria is provided for us by Charles Burney who published in 1771 the journal of his tour through France and Italy which he had undertaken in order to collect materials for his history of music. Burney had a letter to Signor Baretti of Turin and the latter introduced Burney "to Padre Beccaria, for whom, at first sight, I conceived the highest regard and veneration." Burney described Beccaria as follows:

> He is not above forty; with a large and noble figure, he has something open, natural, intelligent, and benevolent in his countenance, that immediately captivates. We had much conversation concerning electricity, Dr. Franklin, Dr. Priestley, and others. He was pleased to make me a present, finding me an amateur (which should always be translated "a dabbler") of his last book, and the syllabus of the Memoire he lately sent to our Royal Society. . . . I left my new acquaintance, impressed with the highest respect and affection for him. I must just mention one particular more relative to this great and good man, which I had from Signor Baretti; that he, through choice, lives up six pair of stairs, among his observatories, machines, and mathematical instruments; and there does everything for himself, even to making his bed, and dressing his dinner.[54]

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[52] Mottelay (ref. 47, *supra*), p. 209.

[53] See Franklin's letter to Dalibard of 29 June 1955, ***Benjamin Franklin's experiments*** (ref. 1, *supra*), pp. 307 ff.; also Smyth, Writings (ref. 25, *supra*), vol. 1, pp. 22, 199, 210; vol. 3, p. 269; vol. 4, pp. 141, 146, 457n.; vol. 5, p. 165n.

[54] Charles Burney, *The present state of music in France and Italy; the journal of a tour through those countries, undertaken to collect materials for a general history of music* (London: T. Becket & Co., 1771), p. 72.

Armed with a recommendation from Beccaria, Burney paid a visit to the Physical Institute at the University of Bologna to see "the Dottoressa Madame Laura Bassi, and met with a very polite and easy reception." Laura Bassi occupies a singular place in the history of 18th-century education, when the presence of ladies on university faculties was rare.[55] Burney described her as "between fifty and sixty; but though learned, and a genius, not at all masculine or assuming." She and Burney talked about the celebrated men of science in Europe, and in particular she expressed great admiration for the English, "in Eulogiums of Newton, Halley, Bradley, Franklin, and others." According to Burney,

> She told me that Signor Bassi, her husband, immediately after Dr. Franklin had proved the identity of electrical fire and lightning, and published his method of preserving buildings from the effects of it, by iron rods, had caused conductors to be erected at the Institute; but that the people of Bologna were so afraid of the rods, believing they would bring the lightning upon them, instead of the contrary, that he was forced to take them down. Benedict XIV, one of the most enlightened and enlarged of the Popes, a native, and in a particular manner the patron, as well as soverign of Bologna, wrote a letter to recommend the use of these conductors; but it was so much against the inclination of the inhabitants of this city, that Signor Bassi desisted entirely, and they have never since that time been used here.[56]

From what we know of the life and personality of Pope Benedict XIV, his action—as described by Burney—is wholly in character.[57] No such letter is to be found in the published correspondence of Benedict XIV,[58] although it may well exist in manuscript, and may have been published in contemporary newspapers or journals.

Incidentally, the husband of Laura Bassi was not "Signor Bassi," as Burney supposed, but rather Giuseppe Veratti. The latter repeated Franklin's sentry-box experiment and is said to have "obtained the electric spark in all weathers, through a bar of iron resting in sulphur";[59] his published works deal with the application of the electric shock to paralytics and the aurora borealis, as well as his investigations of atmospheric electricity.[60]

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[55] Laura Caterina Bassi was not the only woman appointed professor at Bologna at this time; another was the famous mathematician Maria Gaetana Agnesi (the curve known as the "witch of Agnesi" is named after her). Consent to both appointments was given by Pope Benedict XIV; see Ludwig, Freiherr von Pastor, *The history of the Popes*, tr. by E. F. Peeler (London: Routledge and Kegan Paul, 1949 [1950], vol. 35, p. 192. Laura Bassi taught philosophy to Luigi Galvani and influenced him profoundly; see Potamian and Walsh (ref. 50, *supra*), p. 154.

[56] Burney (ref. 54, *supra*), p. 217.

[57] For example, he established a chair of surgery in Bologna and he was generally interested in the sciences. See Pastor (ref. 55, *supra*), vol. 35, ch. 3.

[58] Cf. Emile de Heeckeren, ed., *Correspondance de Benoît XIV* (Paris: Librairie Plon, 1912), vol. 2 [1750–1756].

[59] Mottelay (ref. 47, *supra*), p. 204.

[60] Publications of Veratti are listed or described in Mottelay (ref. 47, *supra*), pp. 186, 204, 213, 264, 384; Giovanni Fantuzzi, *Notizie degli scrittori bolognesi* (Bologna: Nella Stamperia di S. Tommaso d'Aquino, 1794), vol. 9, p. 193 (containing a brief biographical notice); Pietro Riccardi, *Biblioteca matematica italiana*, parte prima (Modena: Società Tipografica Modenese,

No discussion of 18th-century Italian Churchmen and lightning would be complete without mention of Abbé Giuseppe Toaldo, professor of physics at Padua, who introduced the lightning rod into the Venetian Republic. Toaldo published a number of works on lightning and lightning rods [61] and translated several items into Italian, including de Saussure's *Exposition abrégée* . . . of 1771. The lightning rod installation in the beautiful mediaeval cathedral at Sienna (whose tower had been repeatedly struck by lightning) was supervised by Toaldo and, although the local inhabitants regarded the rod with terror and apprehension, it remained in place; on 10 April 1777, the rod carried off a heavy stroke of lightning "without doing the slightest damage even to the gilded ornaments near which it passed. The inhabitants now began to look on the heretic rod with more confidence; and it is an important fact," as Snow Harris reported almost 50 years later,[62] "that this church does not seem to have suffered from lightning since."

The attitude of Pope Benedict XIV, like the introduction of lightning rods on some Catholic churches in the 18th century, indicates that the slowness in adopting the new invention did not proceed from ecclesiastical ban or dogma so much as from the attitude of individual officials who, like their own parishioners, rejected the lightning rod on the basis of personal prejudice or ignorance, just as did their Protestant fellows in England.

MAN'S PRESUMPTION IN ERECTING LIGHTNING RODS—OR CIRCUMVENTING THE DIVINE PROVIDENCE

While we often refer to the 18th century as "the age of enlightenment," we must remember that this phrase applies to the thought of leaders in the realm of the intellect, but obviously not to the vast majority of people. The prevalence of the custom of ringing church bells during storms, and the kind of antagonism to lightning rods which we discussed in the preceding section,[63] indicate that superstition was still strong in the minds of the unenlightened.

1876), vol. 2, p. 594; Serafino Mazzetti, *Repertorio di tutti i professori antichi e moderni della famosa università, e del celebre istituto delle scienza di Bologna* (Bologna: Tipografia di San Tommaso d'Aquino, 1847), p. 318, §3098; Anderson (ref. 44, *supra*), pp. xv, 233 [1755^2], 234 [1757].

[61] Cf. Mottelay (ref. 47, *supra*), pp. 253–254; also Potamian and Walsh (ref. 50, *supra*). The need for rods was strikingly demonstrated in 1767, 17 years after the lightning experiments of Franklin, when the Church of San Nazaro in Brescia was struck; some 200,000 pounds of gunpowder had been stored in the vaults, with no protection from lightning, and we are told that in the explosion "one sixth of the entire city was destroyed, and over three thousand lives were lost." Cf. White (ref. 3, *supra*), vol. 1, p. 368.

[62] Snow Harris (ref. 14, *supra*), p. 97.

[63] About 30 years after the invention of the lightning rod, [acc. to White (ref. 3, *supra*), p. 367] it was reported in Germany in 1783 that during 33 years "nearly four hundred towers had been damaged [by lightning] and one hundred and twenty bell-ringers killed. Schonland (ref. 11, *supra*), p. 8, refers to an edict of 1786, issued by the Parlement of Paris "to make the

In the volume of letters which the Abbé Nollet published in refutation of Benjamin Franklin's electrical ideas, and in which he expressed himself so forcibly in opposition to the use of lightning rods,[64] he applied himself—as Franklin wrote to his friend Cadwallader Colden on 12 April 1753—"to the superstitious prejudices of the populace, which I think unworthy of a Philosopher."

> He speaks as if he thought it Presumption in man to propose guarding himself against the *Thunders of Heaven!* Surely the Thunder of Heaven is no more supernatural than the Rain, Hail or Sunshine of Heaven, against the Inconvenience of which we guard by Roofs & Shades without Scruple.
>
> But I can now ease the Gentleman of this Apprehension; for by some late Experiments I find, that it is not Lightning from the Clouds that strikes the Earth, but Lightning from the Earth that strikes the Clouds. . . .[65]

The last sentence quoted above refers to some experiments which Franklin had made late in 1752 and early in 1753 with the aid of a lightning indicator. The latter consisted of a two-part lightning rod; the upper part was an insulated pointed rod ascending vertically from Franklin's house and having a point at the upper end, and a bell at the lower; the other part of the rod ascended from the ground up into the room, ending in a bell placed a few inches from the bell at the lower terminus of the upper rod. A metal ball, forming a clapper to the bells was suspended between them by means of an insulated string. At the approach of an electrified cloud, the clapper would play back and forth between the bells, thus giving notification of the presence of electrical cloud. This instrument was used by Franklin to show that clouds may be sometimes electrified negatively as well as positively, and in fact almost always negatively.[66]

According to Franklin's theory, the lightning discharge was nothing other than the establishment of electrical equilibrium by the passage of

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custom illegal on account of the many deaths it caused to those pulling the ropes. How necessary this edict was can be judged from figures given in a book published in Munich in 1784 with the cautious title, *A proof that the ringing of bells during thunderstorms may be more dangerous than useful.* The author, Fischer, stated that in 33 years lightning had struck 386 church towers and killed 103 bell-ringers at the ropes. These figures are not surprising when the accounts of lightning striking and damaging church steeples and other elevated structures are examined, for such damage was very frequent." Apparently, the book in question, which I have not seen, was written by Johann Nepomuk Fischer, professor of mathematics at the University of Ingolstaat (1781–86) and chief astronomer at the Mannheim observatory. J. C. Poggendorff, *Biographisch-literarisches Handwörterbuch* (Leipzig: Verlag v. Johann Abrosius Barth, 1863), vol. 1, p. 751, lists this as "Beweiss, dass das Glockenläuten bei Gewittern mehr Schädlich als nützlich sey usw., Münch., 1784."

[64] Cf. ref. 48, *supra.*

[65] "Cadwallader Colden Papers," vol. 4 [1748–1754], *Collections of the N. Y. Hist. Soc.*, p. 382, 1920.

[66] Cf. Smyth (ref. 25, *supra*), vol. 3, pp. 149–153, 193. We would alter Franklin's statement to read "the base" or the "lower part" of the clouds; cf. Schonland (ref. 27a, *supra*, § 6, p. 380).

the electric fluid from a positively charged body (that is, one having an excess of the electrical fluid) to a negatively charged body (that is, one having a deficiency of the electrical fluid). Hence if a cloud were charged negatively, equilibrium (or a state of electrical neutrality) was restored by some electrical fluid passing into it from another cloud (one that was neutral or positively charged), or from the earth. The conclusion from Franklin's theory and his observation that clouds are most often electrified negatively was that the lightning discharge usually must proceed from the earth to the clouds, rather than from the clouds to the earth. This result served as a rationalist basis for dismissing completely any notion of presumption in man's using his ingenuity to circumvent "thunderbolts from heaven," since the bolts came from the earth. The issue of presumption, however, was raised in America as well as in Europe and must be given its due place in any consideration of the prejudices against the introduction of lightning rods.

The members of the "Junto," the society founded by Benjamin Franklin in Philadelphia which later became the American Philosophical Society, were led to ask at a meeting on 18 January 1760: "May we Place Rods on our Houses to guard them from Lightening without being guilty of Presumption?" At this time, Franklin himself was in London and had been since 1756, and one may speculate as to whether this question would have ever been raised had Franklin been in Philadelphia. Be that as it may, the question did come up; and at the meeting of 15 February 1760, the following discussion took place:

> The Company agreed to consider the second Query proposed the 18th of last Month viz Whether we may place iron pointed Rods on our Houses to guard them from Lightening without being guilty of Presumption, and after considering or canvassing the Question they were of Opinion that Rods may be put up to guard our Houses without any Presumption. For tho the rending Peal of Thunder may fill the Minds of the Ignorant with Terror who from an Ignorance of its Cause and their natural Superstition may imagine that it is the immediate Voice of the Almighty and the Streaming Lightening are Bolts launched from his Right Hand and commissioned to execute his Vengeance yet in Reason's Eye Lightening or Thunder is no more an Instrument of Divine Vengeance than any other of the Elements. That it is not always directed to execute divine Wrath appears from hence that it most frequently wastes itself on inanimate Things as Trees, Houses, etc. Indeed the Case is this (as by Experiments appears) it is attracted by Eminences. For wherever a Cloud flying over the Earth which has either more or less of the Electric fluid or Lightening than the Earth, comes so near as to be attracted, a stream of Lightening ensues to restore the Equilibrium, and that stream is conveyed by those Objects which having a Communication with the Earth rise nearest the Clouds. This then being the Case and (thanks to God) it having been discovered that Metal is the best Conveyance and that while it can get that it will follow it without damaging any thing else tho' in the nearest contact with it, so far is it from being Presumption to use this Invention that it appears foolhardiness to neglect it. And if to neglect preventing an Evil when it is in one's power is in some measure to be accessory to the bringing it on, it is hard to say how those persons who are so unfortunate as to have their Houses struck or any of their family hurt by Lightening can acquit themselves of being in some measure guilty. It might be mentioned with what Care we endeavour to guard against the bad Effects of other Elements, what means are used both to prevent & remove Disorders of the Body Plagues & Sickness of every sort, and this without

> any Imputation of Presumption; why then should it be imagined more presumptious in the present Case? But what is said suffices for an answer.[67]

Two aspects of this most reasonable discussion strike the eye of the modern reader. First, there is the well taken point that the divine wrath would hardly be directed at trees, which are often struck by lightning; secondly, since there is no longer any objection to curing human ills, or removing sicknesses from the body, why should not man protect himself from the lightning by using the device which, "thanks to God," it had been vouchsafed to Benjamin Franklin to discover? Far from there being any presumption against God's providence, there was a presumption of guilt against any man who suffered loss or damage to either his house or his family by not taking advantage of the new invention.

One of the participants in the above discussion at the "Junto" was Philip Syng, a silversmith who had collaborated with Benjamin Franklin in the performance of the original experiments. Another of Franklin's collaborators was the Baptist clergyman, Ebenezer Kinnersley, whom Franklin had helped to get an appointment as Professor of English and Oratory at the Academy (which later became the University of Pennsylvania).[68] Franklin thought very highly of Kinnersley and published many of his letters in his own book on electricity. The electrical discoveries of Kinnersley are recorded in Priestley's history of electricity and his fame was sufficiently great for his work to have received the highest praise from the Abbé Beccaria. Franklin helped Kinnersley in writing a pair of public lectures on electricity; these Kinnersley delivered in Boston, Newport, and also in St. John's, Antigua in the West Indies. Kinnersley announced his first Boston lecture in the *Boston Evening Post* of 7 October 1751; the lectures and demonstrations, given at Faneuil Hall, were evidently very popular since they continued until the end of January 1752.

One item in the second of Kinnersley's pair of lectures is of special interest to us; it reads:

> Various Representation of Lightning, the Cause and Effect of which will be explained by a more probable Hypothesis than has hitherto appeared, and some useful Instructions given how to avoid the Danger of it: How to secure Houses, Ships, *etc.* from being hurt by its destructive Violence.[69]

Those who heard Kinnersley's lectures in Boston, therefore, heard about the lightning rod at the end of 1751 or early in 1752, some months before experiment had shown that Franklin's hypothesis had any validity.

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[67] Extract from the MS "Junto Minute Book" in the American Philosophical Library. I gratefully acknowledge the assistance given me by Mrs. Gertrude Hess of the American Philosophical Society Library, who brought to my attention this Junto discussion, and whose wealth of knowledge concerning every aspect of Franklin's career has helped me and others to answer many vexing questions.

[68] Cf. *Benjamin Franklin's experiments* (ref. 1, *supra*), for an account of the life and work of Kinnersley.

[69] The full text of the description of Kinnersley's lectures is reprinted in William Northrop Morse, "Lectures on electricity in colonial times," *New England Quarterly* 7: 363–374, 1934.

The lectures as given in Newport soon after Kinnersley left Boston were evidently identical to those which he had given in Boston; the announcement in the form of a broadside printed by Peter Franklin, dated Newport, 6 March 1752, was merely a reprint of the Boston advertisement.[70]

By the following year, however, a completely new note had been introduced. In a broadside dated "St. John's, April 25, 1753," advertising Kinnersley's lectures in Antigua, the second lecture contained the following items:

> XX. An Experiment, shewing how to preserve Houses, Ships, *&c.* from being ever Struck by Lightning.
>
> XXI. The endeavouring to guard against Lightning, shewn to be not chargeable with Presumption, nor inconsistent with any of the Principles either of natural or revealed Religion.[71]

By this time, the hypothesis of the electrical nature of the lightning discharge had been confirmed by experiments in France, England, and America, and therefore item XX is stated in much stronger language. But item XXI, dealing with presumption, is a novelty. It obviously would not have been necessary prior to the introduction of lightning rods, since the question of presumption actually arose only after men first began to use the lightning rods.

The question of presumption was also raised in the South. *The Virginia Gazette* for 17 October 1766 contained an announcement of "A course of experiments, in that instructive and entertaining branch of natural philosophy, called electricity, to be accompanied with lectures on the nature and properties of the electrick fire," to be presented for "the entertainment of the curious" by William Johnson. Johnson's "course" consisted of two lectures, the first of which was devoted to the principles of electrical science, and the second to lightning. According to the announcement:

> In the second lecture this [electric] fire is shown to be real lightning, by its constantly and invariably producing the same effects as lightning does; in proving and explaining which, most of the effects of lightning will be imitated by the electrick fire, such as killing animals, melting metals, tearing and rending bodies through which it passes; together with many curious experiments, naturally representing the various *phenomena* of thunder storms, accounting for their causes, and explaining their effects. A practical method of preserving ourselves, our houses, and effects, from the destructive violence of lightning, will likewise be shown; the efficacy of which will be demonstrated by such indubitable proofs, from experience, as have not hitherto been exhibited to the world.

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[70] Kinnersley's Newport broadside is dated March 6, 1752, printed by James Franklin. Two copies of this broadside exist. One is in the Rider Collection in the Brown University Library at Providence, described in George P. Winship: *Rhode Island Imprints* (Providence, Preston and Rounds, 1914), p. 13 and there reproduced in full facsimile on the plate facing p. 14. A second copy, in the private collection of Dr. A. S. W. Rosenbach of Philadelphia, formed one of the items in an exhibition held at the Free Library of Philadelphia in 1938. It is described in the catalogue of that exhibition, *The all-embracing Doctor Franklin . . . illustrated by books and manuscripts from the collection of Dr. A. S. W. Rosenbach* (Philadelphia, Free Library of Philadelphia, 1938).

[71] Original in the Library of Congress. It was found among the papers of William Thornton by Chauncey Worthington Ford, who printed the text of it in "New Light on Franklin's Electrical Experiments," *The Nation* **86**: p. 85–86 (1908).

> Those who desire to have their habitations effectually guarded from the fatal violence of one of the most aweful powers of nature (with which this colony in particular has been often dreadfully visited) may learn, from these lectures and experiments, more of the nature and properties of lightning than has been known to mankind until within these few years. They will, at the same time, have an opportunity of being fully convinced that the method proposed for their security, if put in practice, with proper precaution, will be attended with success; and consequently that, instead of having any just objection thereto, from a persuasion of its being presumptuous, we have the utmost reason to bless GOD for a discovery so important and eminently useful. "A prudent man foreseeth the evil, hideth himself; but the simple pass on, and are punished." Prov. xxii 3.
>
> As the knowledge of nature tends to enlarge the human mind, and give us more exalted ideas of the God of Nature, it is presumed that this course will prove to many an agreeable and rational entertainment.[72]

This same announcement was apparently repeated in the issue of *The Virginia Gazette* for 24 October. William Johnson also lectured in Charleston; and an advertisement of his lectures appeared in the *South Carolina and American General Gazette* for 6–13 February 1767.[73]

Benjamin Franklin's South Carolina correspondent John Liming, who made important investigations on human metabolism and who repeated Franklin's lightning-kite experiment,[74] became embroiled in a controversy over presumption. We are told that in order to quiet the good men of Charleston who were alarmed at the possibility of incurring the divine wrath as a result of erecting lightning rods, the *South Carolina and American General Gazette* "suggested raising lightning rods to the glory of God." [75]

THE WINTHROP-PRINCE CONTROVERSY ON LIGHTNING RODS & EARTHQUAKES: & JOHN ADAMS' VIEWS ON THIS QUESTION

The controversy over presumption that has received the most attention from scholars, and is therefore the most well known, centers on the controversy that occurred between Professor John Winthrop of Harvard and the Reverend Thomas Prince of Boston. Since this famous debate has been the subject of many studies by historians, there is no need here to do more than indicate some of the major issues.[76]

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[72] A photostat of the announcement of Johnson's course was provided by the Virginia Historical Society; information about the dates was kindly supplied by Mrs. J. A. Johnston, Assistant Secretary of the Society.

[73] Information kindly supplied by Miss Ellen M. FitzSimons, Librarian, Charleston Library Society.

[74] Cf. *Benjamin Franklin's experiments* (ref. 1, *supra*), p. 72n and pp. 111, 150, 161, 331, 339; also Franklin C. Bing, "John Lining, an early American scientist," *Scientific Monthly* **26**: 249–252, 1928, and the article in the *D. A. B.*

[75] Cf. Bernard Faÿ, *Franklin, the apostle of modern times* (Boston: Little, Brown & Co., 1929), p. 227. The third volume of the original French edition has a valuable bibliography and complete annotation, *Benjamin Franklin: Bibliographie et étude sur les sources historiques relatives à sa vie* (Paris: Calmann-Lévy, Editeurs, 1931), esp. p. 45.

[76] In addition to White (ref. 3, *supra*), see Theodore Hornberger, "The science of Thomas Prince," *New England Quarterly* 9: 24–42, 1936; Eleanor Tilton, "Lightning-rods and the earthquake of 1755," *New England Quarterly* **13**: 85–97, 1940.

The quarrel between Winthrop and Prince was occasioned by the earthquake of 1755 and operated on two separate levels—scientific and theological. Prince's sermon *Earthquakes, the Works of God* (printed in Boston in 1755) contained the following statement:

> The more *Points* of *Iron* are erected round the *Earth,* to draw the *Electrical Substance* out of the *Air;* the more the *Earth* must needs be charged with it. And therefore it seems worthy of Consideration, Whether *any Part* of the *Earth* being fuller of *this terrible Substance,* may not be more exposed to *more shocking Earthquakes.* In *Boston* are more erected than anywhere else in *New England;* and *Boston* seems to be more dreadfully shaken. O! there is no getting out of the mighty Hand of *God!* If we think to avoid it in the *Air,* we cannot in the *Earth:* Yea, it may grow more fatal. . . .[77]

The scientific questions raised by Prince are, therefore, two in number (1) Do lightning rods draw the electrical substance out of the air? (2) Will the electrical substance that is accumulated in one part of the earth (say the neighborhood of Boston) tend to produce earthquakes there?

Strange as it may seem to the modern reader, in the 18th century the theory that lightning might be related to earthquakes was scientifically acceptable. For example, in *The Pennsylvania Gazette* for 15 December 1737, Franklin printed an article about earthquakes in which the opinion was endorsed "that the material cause of thunder, lightning, and earthquakes, is one and the same, *viz.* the inflammable breath of the Pyrites which is a substantial sulphur, and takes fire of itself." [78] Adherents to this theory later proved to be among the first to applaud Franklin's notions on the electrical nature of the lightning discharge.

Some ten years after Franklin had published the article on earthquakes, he began his investigations on electricity and—as we saw earlier—in the paper entitled "Opinions and conjectures, concerning the properties and effects of the electrical matter, arising from experiments and observations, made at Philadelphia, 1749," he summed up his earlier conclusions about the nature of lightning, suggested the lightning rod, and proposed the sentry-box experiment to test the hypothesis that the lightning discharge is an electrical phenomenon. This paper was read at a meeting of the Royal Society of London, where—contrary to

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[77] Thomas Prince, *Earthquakes the works of God and tokens of his just displeasure. . . . And among other things is offer'd a brief account of the natural, instrumental, or secondary causes of these operations in the hands of God. After which, our thoughts are led up to Him, as having the highest and principal agency in this stupendous work. . . . Made public at this time on occasion of the late dreadful earthquake which happened on the 18th of Nov. 1755* (Boston: D. Fowle & Z. Fowle, 1755), "Appendix," p. 23.

This work (Evans 7549) was in part a reprint of an earlier work, having a title of which the first portion was identical (Boston: D. Henchman, 1727; Evans 2946).

[78] Cf. Alfred Owen Aldridge, "Benjamin Franklin and Jonathan Edwards on lightning and earthquakes," *Isis* 41: 162–164, 1950. Aldridge shows that the major part of the article on earthquakes was a word by word transcript from Ephraim Chambers' *Cyclopaedia* . . . (London, 1728).

Franklin's statement in the autobiography—it was not greeted with derision but aroused a considerable amount of interest and discussion.[79] An "Appendix to the *Philosophical Transactions*" was added to the regular publication for 1750; this extra issue (Num. 479) consisted of 57 articles, filling 150 pages, all devoted to the single subject of earthquakes, and apparently occasioned by consideration of the series of violent earthquakes felt in England during the Spring of 1750. Three of these papers were written by the Reverend William Stukeley; one, which had been read before the Royal Society on 22 March 1749, includes the following statement:

> We had lately a very pretty Discourse read here Nov. 16, 1749, from Mr. *Franklyn* of *Philadelphia*, concerning Thundergusts, Lights, and like Meteors. He well solves them by the Touch of Clouds, rais'd from the Sea (which are non-Electrics), and of Clouds rais'd from Exhalations of the Land (which are electrify'd): That little Snap, which we hear, in our electrical Experiments, when produc'd by a thousand Miles Compass of Clouds, and *that* reechoed from Cloud to Cloud, the Extent of the Firmament, makes that Thunder, which affrightens us. From the same Principle I infer, that, if a non-electric Cloud discharges its Contents, upon any Part of the Earth, when in a high electrify'd State, an Earth quake must necessarily follow.[80]

Similar thoughts to Stukeley's were included in a discussion of earthquakes by Stephen Hales, although he did not mention Benjamin Franklin. It will be noted that Stukeley gave Franklin's hypothesis serious consideration in 1750, long before it had been verified by experiment.

During 1750 and 1751 the London magazines devoted much space to letters on the cause of earthquakes. Some writers, agreeing with Stukeley's position, approved the hypothesis that lightning may cause earthquakes, or at least that the cause of both is the same, whereas others expressed violent disagreement. In the *Gentleman's Magazine* for October 1750 there was published a letter by "E. A." reading in part as follows: "In the philosophical solution which I propose to give of this alarming incident, the reader will find no mention made of any such words as *nitre*, *sulphur*, *particles*, *explosion*, or *electrical fire*, which our modern philosophers make use of on all occasions, in explaining all of the phenomena that appear in the heavens above, or are felt in the earth beneath." In the issue of the same magazine for August 1751, "W. M." objected very strongly to Stukeley's theory, and stated: "I adhere still to the *old creed*, and must believe . . . that the occasion of all earthquakes arises from *fire*, *air*, or *water*, separately or conjunctly. . . ." Since Cave, who published the *Gentleman's Magazine*, was also the publisher of Franklin's book on electricity, it is not surprising to find a note added to the above letter explaining that Stukeley "takes notice of a curious discourse from Mr. *Franklin* of Philadelphia (. . . read at the Royal Society, and since printed by E. Cave) concerning thunder gusts, lightning, the Northern lights, and like meteors; all of which are solved by the doctrine of electricity."

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[79] Cf. *Benjamin Franklin's experiments* (ref. 1, *supra*), intro., ch. 2.

[80] Stukeley's articles in the *Philosophical Transactions* were reprinted in London in 1750 under the title, *The philosophy of earthquakes*. Stukeley presented a copy of the third edition (1786) to Franklin, with the inscription "To Benjamin Franklin Esq. Father of Electricity. The Author." This copy, at present in the Boston Public Library, is described in Catalogue No. 943 of Davis & Harvey (auctioneers of Philadelphia), compiled by Stan. V. Henkels, *The extraordinary library of Hon. Samuel W. Pennypacker, Governor of Pennsylvania, . . . to be sold Thursday afternoon and evening, Dec. 14, 1905.*

So widespread was the speculation that earthquakes might be explained in terms of the action of electricity that Dr. John Fothergill, in his preface to Franklin's book on electricity, felt the necessity of showing that Franklin's ideas about the cause of lightning were based on empirical evidence and were not merely part of the general speculation of the time. He pointed out that "from the similar effects of lightning and electricity," Franklin had been "led to make some probable conjectures on the cause of the former; and, at the same time, to propose some rational experiments in order to secure ourselves, and those things on which its force is often directed, from its pernicious effects." Fothergill emphasized that Franklin's discussion of lightning rested on a sound scientific basis and actually led to a series of proposed experiments whereby the truth of his hypothesis might be tested. Thus Franklin's work was to be contrasted to the unbridled speculations of those who would attribute earthquakes to electricity. "It has, indeed, been of late the fashion to ascribe every grand or unusual operation of nature, such as lightning and earthquakes, to electricity," wrote Fothergill, "not, as one would imagine from the manner of reasoning on these occasions, that the authors of these schemes have discovered any connection betwixt the cause and effect, or saw in what manner they were related; but, as it would seem, merely because they were unacquainted with any other agent, of which it could not positively be said the connection was impossible." [81]

In any event, despite the hostility [82] to the theory that the cause of lightning and earthquakes is the same, the theory was given serious discussion during the 1750's. After the experiments in 1752 had confirmed Franklin's hypothesis about the electrical nature of the lightning discharge, the theory that earthquakes are caused by an accumulation of lightning had been given a kind of *modus operandi* in the omnipresent electrical fluid; it seemed, therefore, much more worthy of serious consideration than it had been up until that time. Hence, when the Reverend Thomas Prince of Boston published his pamphlet in 1755, a number of people endorsed the theory that there is one single cause of lightning and earthquakes; since Franklin's experiments had indicated that the cause of the lightning discharge is the electrification of clouds, earthquakes too must be produced by the action of the electrical fluid.

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[81] *Benjamin Franklin's experiments* (ref. 1, *supra*), pp. 166–167.

[82] Some information on this hostility, and also on the reception of Franklin's ideas by Stukeley may be found in an entry in the latter's diary, under the date of Dec. 1752, giving a brief survey of the history of electricity from 1704 to 1752: ". . . Nov. 9, 1749, Mr. Collinson gave into the Royal Society Mr. Franklin, of Philadelphia, his discourse on thunder, lightning, fireballs, aurora borealis, and the like meteorological phaenomena, which he judiciously solves from electricity. 21 Dec. following, Mr. Collinson gave in another paper from Mr. Franklin on electricity. All these were printed, and a copy sent to France, which has excited the French philosophers, under the personal inspection of the monarch, to try so many experiments proving Mr. Franklin's doctrines of the cause of lightning, thunder, &c., from electricity. 15 Mar., 1749–50, after 2 shocks of earthquake we felt at London, I gave in a paper tending to prove that earthquakes are the effect of an electrical vibration of the surface of the earth, which has since been admitted by the French philosophers, though they seem to attribute it to Dr. Stephen Hale[s]. My paper was postponed by reason of other discourses till the next week, 22 March, when it was read, but with great opposition. 29 Mar., 1750, I gave in a second paper of 16 quarto pages, on earthquakes, confirming my former sentiments. It was deferred to the Thursday following, 5 April, 1750, when it was read. After it Dr. Hale's paper was read. . . . Dr. Hale[s] and Mr. Flamsted before him make an approach toward electricity

The first part of Prince's pamphlet of 1755 is a slightly revised version of an earlier discourse of 1727. In the meanwhile, as we just saw, Franklin's electrical discoveries had considerably altered the situation; hence, in 1755 Prince felt it necessary to add an appendix:

> Since my composing the foregoing Discourse, the sagacious Mr. *Franklin*, born and brought up in *Boston*, but now living in *Philadelphia*, has greatly surpriz'd the World with his Discoveries of the *Electrical Substance*, as one great and *main Instrument* of *Lightning* and *Thunder:* not I presume as if it excludes the Operation of *sulphureous, nitrous, mineral, watery* and *airy* Substances; but as a principal Means of exciting them in Action, and of working with them those Effects: and with good Reason suggests, that as this *Electrical Substance* seems to be one of the mightiest Agents we know of among material Substances in this lower World, so extremely subtil as to peirce thro' the most solid Iron with greatest Ease and Rapidity, and the *Earth* is the grand Source from whence it rises and to which it returns; it seems very likely that this *Electrical Substance*, with the *Others* mentioned, is a *principal Instrument* in producing *Earthquakes.*[83]

Although Prince seems to have relied on Franklin for support of his ideas, the sentiment was not one which Franklin would have endorsed.

In the extract just quoted, Prince suggested that Franklin's explanation of the cause of lightning merely advanced electricity "as one great and *main Instrument* of *Lightning* and *Thunder*"; as if Franklin had not thereby excluded the operation of other substances which were "*sulphureous, nitrous, mineral, watery* and *airy.*" Prince was in error, because Franklin certainly believed that the lightning discharge itself was nothing more than the passage of electrical fluid from one cloud to another, from a cloud to the earth, or from the earth to a cloud; thunder, however, as an acoustic phenomenon, would probably have been explained in the terms of the agitation of air particles.

After reading Prince's pamphlet, Winthrop composed a reply in the form of *A Lecture on Earthquakes*, which he read in the chapel of Harvard College on 26 November 1755 and then published. Since the

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being the cause of earthquakes, but do not directly attribute them to it." (Extract from "The family memoirs of the Rev. William Stukeley . . . ," vol. 2, *Publications of the Surtees Society* **76**: pp. 378–379, 1883.) Cf. Stuart Piggott, *William Stukeley, an eighteenth-century antiquary* (Oxford: Clarendon Press, 1950).

[83] Ref. 77, *supra*, p. 20.

purpose of the present article is to deal with the question of lightning rods, there is no need to go into Winthrop's discussion of the theory of earthquakes. As a good physical scientist, he abhorred the notion that lightning is a cause of earthquakes. We may confine our attention to the "Appendix, concerning the operation of electrical substances in earthquakes; and the effects of iron points."

Winthrop followed the example set by Fothergill in the latter's preface to Franklin's book on electricity: "Philosophy, like everything else, has had its fashions, and the reigning mode of late has been, to explain everything by *Electricity*." It was not very long ago that "we were amused with pompous accounts of the wonderful effect of electricity in the practice of physic," electricity having been supposed to be the cure-all for "gout, blindness, deafness, dumbness, and what not! . . . Now it seems, it is to be the cause of earthquakes."

> . . . It is true, the very ingenious Mr. Franklin of *Philadelphia* has, with singular sagacity, and, in my opinion, with happy success, accounted this way for the phaenomena of thunder and lightning; and had made discoveries upon this subject, which are not only extremely curious in speculation, but of high importance in practice. But this is no argument, that electricity is also the cause of earthquakes.[84]

As a sample of Prince's misunderstanding of the subject of electricity, Winthrop quotes the following from page 31 of Prince's tract:

> [the] *Electrical Substance* subsists and moves to and fro in *different Parties* or *Collections* in the *Bowels* of the *Earth*, as well as in the *Clouds* of the *Air*. And so waving about in *different Parties* in the *Earth* below, though by *Divine Direction*, and *surrounding other Substances*, as in the *Air* above; when a *greater* Party comes within the striking Distance of *another*, a *Shock* is immediately effected: and in *Proportion* to the *Quantities* of those several Parties, and the *other Substances surrounded by them*, is the *Shock* in the *Earth*, either *less* or *greater*.

In reply says Winthrop,

> The two cases of lightning and earthquakes are no way parallel; . . . the electric substance, when in the bowels of the earth, is in circumstances essentially different from what it is, when in the clouds of the air; [this] will, I think, plainly appear, by taking a brief view of the known laws of electricity, so far as they can be thought to relate to this subject.[85]

Winthrop's outline of the laws of electricity is of the greatest interest since it is one of the best statements of the principles of electrical knowledge according to Franklin's system of which I know. Winthrop was familiar with Franklin's writings and experiments, many of which he had performed for his classes at Harvard College, using the electrical apparatus which Franklin had helped the College to obtain.[86] Winthrop was not only a trained scientist, but he knew at first-hand the exact experimental basis of Franklin's theoretical speculation. In other words, he was able to read Franklin's statements in their empirical background and to limit properly the extensions and applications to be made of them. Prince, on the other hand, took certain dicta of Franklin out of context, rephrased them in his own words, and then tried to apply them to the theory of earthquakes. Due to the limitations of his empirical experience in the actual performance of laboratory experiments, his applications of Franklin's theory were faulty and he extended the theory in a way that was not in keeping with the Franklinian principles of electrical action.

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[84] John Winthrop, *A lecture on earthquakes*; *read in the chapel of Harvard College in Cambridge, N. E. November 26th 1755* (Boston: Edes & Gill, 1755).

[85] *Ibid.*, p. 33.

[86] Cf. I. Bernard Cohen, *Some early tools of American science* (Cambridge: Harvard University Press, 1950).

Jared Eliot wrote to Ezra Stiles on 24 March 1756: "I think Mr. Winthrop has laid Mr. Prince flat on back, and seems to take some pleasure in his mortification. The Professor has in my opinion given the best Summary of Laws of Electricity that I have ever seen . . ."[87] In this summary, Winthrop laid stress on the way in which bodies may become charged, and how bodies which are charged may give their charge to other uncharged bodies. He also pointed out in great detail the difference between conductors and non-conductors and the way in which conductors lose their charge when grounded.

> It is easy now to see [wrote Winthrop], that, though lightning may be accounted for upon these principles, earthquakes cannot. For clouds, which are collections of watery, that is, of non-electric vapors, being *intirely supported and surrounded by air*, which is an electric *per se*, are capable of having more or less than their natural quantity of the electric substance. And therefore, when a cloud, containing more or less than its natural quantity of the electric substance, approaches the earth; or when two clouds, containing unequal quantities of this substance, approach one another; the consequence will be, a discharge of electric substance from that body which contained the most of it, into that which contained the least, till it becomes equally divided between them; which discharge will be accompanied with a flash of lightning and clap of thunder. But where is the *analogy* between this case in the air, and what may be supposed to pass in the bowels of the earth, to cause earthquakes? To make out any thing like an analogy, we must suppose, *first*, two huge non-electric bodies under ground, which for some earthquakes, must be hundreds, if not thousands, of miles in extent; and, *secondly*, that each of these non-electrics is *intirely supported and surrounded by electrics* per se. The *first* of these suppositions has no difficulty in it; because this terraqueous globe consists almost wholly of non-electrics; but where to find such electric supporters for these vast conductors, as are required in the *second*, is a point, I humbly conceive, attended with very great difficulty. And yet, without this, it is impossible that either of these non-electrics can have more or less than its own natural quantity of electric substance.

Prince had pointed out that "as an equal distribution of this substance in the clouds produces no lightning, . . . so neither will an equal distribution thereof in the earth produce any concussions there, but an unequal distribution in the earth may cause an earthquake." [88] Winthrop, at the end of his summary of the Franklinian principles of electricity, concluded, "that there can be no 'unequal distribution of this substance in the earth;' and consequently, by this gentleman's own confession in Page 20, 'nothing to produce any concussions there.'" In other words, since the earth is a conductor rather than a non-conductor, Winthrop demonstrated that any excess of electricity "thrown" into the earth at a given place, whether through the action of lightning rods or in any other way, would not remain there; it would instantly "spread itself" so that there would no longer be a concentration of charge in one place. Since there seemed to be no possibility of having unequal distribution of charges ("electric substance") in the earth, there was no way in which electricity accumulating in the earth could cause an earthquake.

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[87] Cf. Franklin Bowditch Dexter, *Extracts from the itineraries and other miscellanies of Ezra Stiles . . . , with a selection from his correspondence* (New Haven: Yale University Press, 1916), pp. 595–596.

[88] Ref. 77, *supra*, p. 20.

Having disposed of Prince's theory that the electric fluid can produce earthquakes, Winthrop next turned to an examination of Prince's statement about the action of lightning rods. Although this part of his attack must seem supererogatory to us, Winthrop felt that if Prince's condemnation of "points" were to go unanswered, the effect would be to "fill with unnecessary terror the minds of many persons." Also, it would tend to discourage the use of "iron points" which were "a means of preventing many of those mischievous and sorrowful accidents, which we have so often seen to follow upon thunder-storms."

Winthrop found six fundamental errors in Prince's discussion. The first two "errors" relate to the action of "points" in drawing electrical fluid into the earth. According to Winthrop, Prince was in error in stating that they "draw the electrical substance out of the *air*." The air is an "electric *per se*," or non-conductor, and the points draw the electrical fluid only from "non-electrics," or conductors such as metals or clouds. Furthermore, the points do not, as Prince implied, draw electrical fluid to the earth by a "*constant and perpetual action*," but draw electrical fluid from the clouds only when the clouds have an excess of electrical fluid relative to the earth. Although Winthrop's logic was good, his knowledge was imperfect. Dry air was supposed to be an "electric *per se*," but moist or humid air was plainly a "non-electric." In addition, a number of experiments made with the sentry-box apparatus designed by Franklin had confirmed the discovery (made by Le Monnier [89] soon after the Marly experiments of May 1752) that a pointed, insulated rod will show signs of electrification even if there are no clouds overhead; the generally accepted conclusion being that such a rod will in fact draw electrical fluid out of the air, as well as out of electrified clouds, though in smaller quantities.

So much for the scientific level of the controversy. Let us now turn to theology. One of the topics of controversy between Winthrop and Prince reminds us of Luther's opinion about the use of bells to ward off the action of demons in the air. Although Luther probably never doubted that storms of various kinds are produced by devils, he apparently "regarded with contempt the idea that the demons were so childish as to be scared by the clang of bells." [90] Winthrop wrote:

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[89] Cf. the letters of the Abbé Mazéas to Stephen Hales, *Phil. Trans. Roy. Soc.* **47**: 536. Cf. Priestley (ref. 12, *supra*), vol. 1, section xi, pp. 421 ff.

[90] White (ref. 3, *supra*), vol. 1, p. 348.

> I should think, though with the utmost deference to superior judgments, that the pathetic exclamation, which comes next, might well enough have been spared. "O! there is no getting out of the mighty hand of God!" For I cannot believe, that in the whole town of *Boston*, where so many iron points are erected, there is so much as one person, who is so weak, so ignorant, so foolish, or, to say all in one word, so atheistical, as ever to have entertained a single thought, that it is possible, by the help of a few yards of wire, to "get out of the mighty hand of God."

Prince was more concerned with men's souls than with the principles of science. Yet, since he was sure that Winthrop had misunderstood his aim, he replied in a letter dated 15 January 1752, published in the *Boston Gazette* of 26 January. Prince's design

> was *not* to prove that there *must* be admitted a *newly supposed* material Cause, viz. of the *Electrical Fire or Substance*, as either the *only*, or even the *principal*, or even *any* natural Means or Instruments of *Earthquakes;*—I say, *This* was *not* my Design, nor do I, nor did I assert it: I only supposed, that from Mr. *Franklin's* Discoveries—*It seems very likely*, that *This Electrical Substance, with the others mentioned*, is *a principal Instrument* in *producing Earthquakes*. And upon *this Supposition*, or *supposing it may be* a principal *Instrument* in *Concurrence with others* mentioned; *my main Design* was to shew, that in all its Actions, *this Substance* also must act by Powers derived from and directed by that same omnipresent, perfectly intelligent, spontaneous and almighty Being we call by the Name of God; tho' according to his usual Ways of acting in his present Course of Nature: And by several pleasing Passages in Mr. *Winthrop's* Lecture; I doubt not but that in my asserting the Agency of God in all the Operations of the *Electrical* Substance, I have this learned Philosopher fully concurring with me, and will be ready to make it vastly clearer than I have attempted; and with a brighter Evidence:—But I was going to say, that as Mr. *Professor* has unhappily *mistaken me* in *several Parts* of my said *Appendix;* notwithstanding all his *granted Premisses* about *Electrics* and *Non-Electrics;* I cannot yet see that he has clearly proved this Conclusion, *that there can be no unequal Distribution of this Electrical Substance in the Earth or Terraqueous Globe:* And therefore I should have made some *Remarks* and put some *Questions* to Him, as a free Enquirer after Truth, for the further Elucidation of this curious Matter.

However, concluded Prince, "*for the present*, I had rather be apprehended by his Readers to be *mistaken* in a Point of *Philosophy;* than by entering into a more particular Enquiry into the *natural Causes of Earthquakes*, in this extraordinary Season." Too much attention to the natural causes of earthquakes would divert the public mind from "*Matters* of *infinitely greater Moment*,"[91] that is, the warning from Almighty God to the inhabitants of the sinful city of Boston![92]

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[91] On the doctrine of "divine providences" in New England theology, the interpretation of various types of natural events as signs and portents of God's will, see Perry Miller, *The New England Mind* (New York: The Macmillan Co., 1939), esp. ch. 8, "Nature"; Clifford K. Shipton, "The New England clergy of the 'Glacial Age,'" *Publ. of the Colonial Soc. of Mass.* **32**: 24–54, 1936.

[92] Winthrop wrote a reply to Prince's letter, issued as a little pamphlet, *A letter to the publishers of the Boston Gazette, &c. Containing an answer to the Rev. Mr. Prince's letter inserted in said Gazette* (Boston: [n. p.], 1756).

Josiah Quincy, *History of Harvard University* (Boston: Crosby, Nichols, Lee & Co., 1860), vol. 2, pp. 219–220, relates that in 1770, "religious scruples were again raised against these protecting instruments, by representing 'thunder and lightning to be "tokens of the Divine displeasure," and that it was a degree of impiety to endeavor to prevent them from doing their full execution.' Professor Winthrop again appeared in defence of the invention of Franklin, by publishing a dissertation, adapted to counteract these scruples, and showing, that 'Divine Providence did not govern the material world by immediate and extraordinary inter-

The earthquake which had started the Prince-Winthrop controversy had been very severe. John Adams, recently graduated from Harvard College, recorded in his diary that "we had a very severe shock of an earthquake. It continued near four minutes. I was then at my father's house in Braintree, and awoke out of my sleep in the midst of it. The house seemed to rock and reel and crack, as if it would fall in ruin about us. Chimneys were shattered by it within one mile of my father's house." In John Adams' library, now in the Boston Public Library, there is a copy of Winthrop's lectures on earthquakes which had been presented to young Adams as a gift. In this book, as in many others in his library, Adams wrote a number of comments of his own. These have been published by Zoltán Haraszti, Keeper of Rare Books in the Boston Public Library; they tell us much about contemporary opinion.[93]

After reading Winthrop's statement that he did not believe there was in Boston "one person so weak, so ignorant, so foolish, or to say all in one word, so atheistical," to have thought it possible to "get out of the mighty hand of God" by the use of a few yards of wire, Adams wrote:

> This Exclamation was very popular, for the Audience in general like the rest of the Province, consider Thunder and Lightning as well as Earthquakes, only as Judgments, Warnings &c and have no Conception of any Uses they can have in Nature.—I have heard some Persons of the highest Rank among us, say that they really thought, the Erection of Iron Points was an impious Attempt to robb the Almighty of his Thunder, to wrest the Bolt of Vengeance out of his Hand; and others, that Thunder was designed as an Execution upon Criminals, that no Mortal can stay. That the Attempt was foolish as well as impious.—And no Instances, even those of Steeples struck, where Iron Bars have by Accident conveyed the Electricity as far as they reached without Damage, which one would think would force Conviction, have no Weight at all.

On the final blank leaf of Winthrop's lecture, Adams wrote the following thoughts about lightning:

> This Invention of Iron Points to prevent the Danger of Thunder has met with all that Opposition from the Superstitions, Affectations of Piety, and Jealousy of New Inventions, that Inoculation to prevent the Danger of the Small Pox, and all other usefull Discoveries, have met with in all Ages of the World.—I am not able to satisfy myself, whether the very general if not universal Apprehension of Thunder, Earthquakes, Pestilence, Famine &c are designed merely as Punishments of Sins and Warnings to forsake, is natural to Mankind, or whether it was artfully propagated, or whether it was derived from real Revelation.

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positions of power, but by stated general laws;' and that it is as much 'our duty to secure ourselves against the effects of lightning, as from those of rain, snow, or wind, by the means God has put into our hands.' " At this time, Winthrop wrote to Franklin (26 October 1770): "I have on all occasions encouraged . . . your . . . lightning rods . . . in this country, and have the satisfaction to find that it has not been without effect. A little piece I inserted in our newspapers last summer induced the people of Waltham (a town a few miles from hence) to fix rods upon their steeple, which had just before been much shattered and set on fire by lightning. They are now becoming pretty common among us, and numbers of people seem convinced of their efficacy," *Proc. Mass. Hist. Soc.* **15**: 11–13, 1876–77.

[93] This and the following quotations from Adams may be found in Zoltán Haraszti, "Young John Adams on Franklin's iron points," *Isis* **41**: 11–14, 1950. Cf. Z. Haraszti, *John Adams & the prophets of progress* (Cambridge: Harvard University Press, 1952).

A post-script noted:

> An Imagination that those things are of no Use in Nature but to punish and alarm and arouse Sinners, could not be derived from real Revelation, because it is far from being true, tho few Persons can be persuaded to think so.

We may conclude this section with another extract from Adams' diary, under the date of either the third or fourth of December 1758:

> The other night I happened to be at the Doctor's with Ben Veasey; he began to prate upon the presumption of philosophy in erecting iron rods to draw the lightning from the clouds. His brains were in a ferment, and he railed and foamed against those points and the presumption that erected them, in language taken partly from Scripture and partly from the disputes of tavern philosophy, in as wild, mad a manner as King Lear raves against his daughter's disobedience and ingratitude, and against the meanness of the storm in joining with his daughters against him in Shakespeare's Lear. He talked of presuming upon God, as Peter attempted to walk upon the water; attempting to control the artillery of heaven—an execution that mortal man can't stay—the element of heaven; fire, heat, rain, wind &c.

CONCLUSION

Looking back on the 18th-century prejudices against lightning rods, the 20th-century reader is all too apt to believe that in this field we have made progress—at the very least, he is apt to feel superior to those who used to ring church bells at the onset of a storm. Yet even today the number of buildings with adequate lightning protection is but a small fraction of those that require rods. Many readers may reply that while the danger from a lightning stroke is possibly very great, the terrors experienced in the past in the face of storms were a result of over-exaggeration, since the probability of any given house being struck is so small as to make such an event virtually impossible. The accumulated evidence does not support such a viewpoint.

In 1879 Richard Anderson [94] collected a great mass of statistical information on lightning damage; the list of public buildings alone that had been damaged or destroyed by lightning during the preceding century occupied ten pages of print. In Austria during the eight-year period between 1870 and 1877, *1,702* fires had been reported as caused by lightning out of a total of *40,128;* in Bavaria, during the thirty-one years from 1843 to 1873, *1,355* persons had been killed by lightning; in Sweden, during the sixty-two year period from 1816 to 1877, *860* persons had been reported as killed by lightning; in France, during the thirty-year period from 1834 to 1863, *2,038* persons had been struck dead by lightning; in European Russia [that is, "dans les 49 gouvernements de la Russie Européenne, sans compter la Finlande et les gouvernements du ci-devant royaume de Pologne"], during the five-year period between 1870 and 1874, *2,161* persons had been killed by lightning and *4,192* fires had been reported as caused by lightning; in Prussia, during the nine-year period from 1869 to 1877, *1,004* deaths had been reported as caused by lightning; while in England, it was estimated that the number of persons killed each year by lightning was over one hundred.

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[94] Reference 44, *supra*, pp. 169–175.

In a book published two years ago, B. F. J. Schonland, one of the foremost scientists in the field of lightning research, was forced to conclude that "lightning still takes a considerable toll of unprotected property in the country from which the rod came." [95] Lightning was given the sixth place in importance among the causes of fire by the United States National Board of Fire Underwriters in 1921; and the annual direct loss of property due to lightning was estimated as being somewhere between twelve and fifteen million dollars per annum.[96] In the state of Iowa alone, lightning was the cause of 924 fires during the five-year interval between 1919 and 1924. Of these, 95 per cent occurred in buildings without lightning-rod protection. (The failure of the rods to afford protection in the other 5 per cent may be attributed to faults in installation, a warning that despite the proved efficiency of lightning rods, they need expert care.) [97] The magnitude of the problem is revealed in the following data: there are some 16,000,000 thunderstorms throughout the whole earth during an average year, or some 44,000 per day; since each storm has a duration of about one hour, there are, in different parts of the world, some 1800 storms in progress at any given moment; the number of lightning flashes taking place in any given second is, on the average, about 100; a complete flash usually represents a discharge of 20 coulombs, although values as high as 160 coulombs have been observed; a single stroke usually represents a discharge of from 2 to 10 coulombs, but the most common peak current in the return stroke is 30,000 amperes, while the greatest value ever observed was 200,000 amperes.[98]

Our negligence in not erecting lightning rods is hardly due to bravery; most readers probably have at least one member of their family who is to some degree frightened of thunder and lightning. The fright may not be sufficient to make necessary the construction of the Franklin bed for which Dr. Burney yearned while in Bavaria in the 18th century, but it may be sufficient to cause severe anxiety during a storm. This kind of anxiety is not always allayed by the presence of a lightning rod; on the contrary, the very sight of a lightning rod—or even the knowledge that a lightning rod is attached to the house—may in itself be a cause of further anxiety of the very same sort that plagued so many people in the 18th century,[99] an apprehension that the rod may invite destruction to those whom it is supposed to protect. This fear is, of course, wholly irrational; the evidence accumulated during the past two hundred years proves conclusively that a properly installed lightning rod does not invite destruction, but will provide protection from the lightning.

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[95] Reference 11, *supra*, p. 101. "The effectiveness of the rod in the case of houses and barns is still not fully appreciated, and it has been estimated that not more than one in five of the buildings in the United States which are liable to damage by lightning are protected in any manner against it."

[96] *Ibid.*

[97] *Ibid.*

[98] *Idem*, pp. 59, 99.

[99] One of the most famous cases of the popular fear of lightning rods being greater than any possible fear of the lightning itself occurred in France in 1780–1784, when M. de Vissery de Bois-Valé erected a lightning rod on his house at St.-Omer. His neighbors instituted legal

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proceedings and forced him to remove the offensive object. M. de Vissery appealed and eventually won the right to restore the rod. The trial was significant in that the leading scientists of France were drawn into fray to defend the use of rods, while the only major "scientific" opposition came from Jean-Paul Marat (*l'ami du peuple*) who believed that the protective power of lightning rods had been exaggerated and that they were dangerous; he took advantage of the occasion to take up arms against "official" French science as represented by the Académie Royale des Sciences, which had refused to admit him to membership. [Cf. J. P. Marat, *Recherches physiques sur l'électricité* (Paris: Imprimerie de Clousier, 1782, pp. 364 ff.; "De la foudre, & des moyens de se garantir de ses atteintes," *Calendrier intéressant pour l'année 1783, ou Almanach physico-économique* (Bouillon: Aux dépens de la Société Typographique, 1783), pp. 6–43].

Interest in this trial is augmented by the fact that the final plea in the appeal was made by Maximilien Robespierre, then a budding young lawyer; the publication of his *plaidoyers* and his skill in this affair brought him a considerable measure of fame. The best account of the whole affair is: Charles Vellay, "Robespierre et le procès du paratonnerre (1780–1784)," *Annales Révolutionnaires* **2**: 25–37, 201–219, 1909. M. Vellay concludes: "A Arras, le procès du paratonnerre avait donné à Robespierre une place considérable. De ce jour, il fut connu de tous, presque célèbre. Dès lors, d'année en année, de plaidoirie en plaidoirie, sa renommée et son influence grandissent ensemble. Certaines causes, qui touchent au domaine politique ou au domaine social, lui donnent l'occasion d'affirmer quelques-uns des principes qu'il développera plus tard sur une autre scène. Et cinq années seulement se sont écoulées depuis le procès de M. de Vissery, quand la convocation des États-Généraux ouvre devant lui la voie nouvelle où l'attendent des triomphes plus éclatants encore, mais plus tragiques." Robespierre's *plaidoyers* are reprinted in Victor Barbier and Charles Vellay, editors, *Ouevres complètes de Maximilien Robespierre* (Paris: Aux Bureaux de la Revue Historique de la Révolution Française, 1910), vol. 1, pp. 19–119. Robespierre based his plea, in part, on the scientific evidence favoring the use of rods, but also on the need for progress—"Les Arts et les Sciences sont le plus riche présent que le Ciel ait fait aux hommes; par quelle fatalité ont-ils donc trouvé tant d'obstacles pour s'établir sur la terre?" (*Op. cit.*, vol. 1, p. 25.) As to fear of presumption, "Ne craignons pas non plus que le Ciel regarde cette démarche, comme une tentative audacieuse pour braver son courroux, et pour lui ôter les moyens de punir nos crimes.

"Croyons-nous donc que le Tout-Puissant aît besoin de ce météore qui nous épouvante, et que, sans lui, son bras désarmé ne puisse plus nous atteindre? Croyons-nous que les nuages soient ses arsenaux; que, semblable à ces dieux qu'enfanta l'imagination des Poëtes, il soit sans cesse environné de carreaux; que le tonnerre s'élance, quand il s'irrite; qu'il revienne, quand il s'appaise? Pensons-nous que tous les mouvemens qu'imprime au fluide électrique sa tendance à l'équilibre, soient autant de présages qui annoncent à la terre la colère du Ciel, et que s'il rencontre, sur son passage, nos maisons et nos édifices, il aît reçu de l'Eternel un ordre particulier de les frapper.

"Bannissons ces vaines terreurs: assez de maux nous affligeront toujours: ne craignons pas que le Ciel s'irrite des efforts que nous ferons pour les soulager. Ne nous rendons pas plus malheureux qu'il ne l'a lui-même voulu; rendons grâces plutôt à sa bonté, qui nous a elle-même inspiré l'idée de nous dérober à un fléau, si long-tems funeste à l'humanité: bénissons cette Providence bienfaisante qui, après nous avoir donné les *simples* pour guérir nos maladies, nous présente aujourd'hui des conducteurs électriques pour nous soustraire aux ravages de la foudre." (*Idem*, pp. 70–71.) Robespierre's letter to Franklin, presenting him with a copy of the *plaidoyers* is to be found in the Library of the University of Pennsylvania; it is printed in *Annales révolutionnaires* **2**: 215, 1909.

The anxiety produced by lightning rods is not based on a knowledge of the action of pointed conductors, but seems to be rather a manifestation of a common fear that a dreadful fate lies in store for any one who dares to tamper with the larger and more potent forces of nature. We have all seen this kind of anxiety manifested in relation to the atom bomb—not in the genuine fear of such a bomb landing in one's back yard so much as a vague apprehension that the production of atomic explosions will have some kind of undefined dire consequences for the whole human race: perhaps crops will not grow in certain regions, the climate may be altered with deleterious results, the earth itself may disintegrate, and so on. In the same way, there is much worry over our successful rain-making efforts: will we take the moisture out of the air and prevent later natural and plentiful rains and so produce a kind of quasi-permanent drought? Will not *DDT* produce, in the end, a more horrible form of insect life which will do more damage than those insects with which we are now familiar, or perhaps kill off all the useful insects and leave only those that are pests or disease-carriers, or perhaps kill off all the insects and rob nature of her means of pollination? Again, when the antibiotics have "successfully" eliminated from the scene all known disease-producing micro-organisms, will we not then encounter a new type of micro-organism over which we will have no control whatever and which will produce more horrible diseases than any we have ever known?

V.
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The idea that man, vis-à-vis the forces of nature, can go just so far and no further, is as old as civilization itself. The taboos of primitive people and the mythology of antiquity alike bear witness to concern about the limits of man's possible activity. We all remember the myth that is concerned with the flight of Icarus with the aid of wings fashioned of wax and feathers; he rose up in the air higher than a man may go, and his punishment was that the wings were melted by the sun's heat and he plummeted to earth and was destroyed. Closer to the topic of this essay is the myth of Prometheus, who may be regarded as the founder of civilization; he stole fire from the heavens and bestowed it on man, together with the arts that made its control possible. In anger at this act of presumption, Zeus had Prometheus bound to Mt. Caucasus; among the punishments which ensued, was that a vulture came every day to devour his liver, which grew again during the night so that the torture might go on indefinitely.[100]

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[100] For an analysis of the Prometheus myth, see Sigmund Freud, *Civilization and its discontents*, trans. by Joan Riviere (London: The Hogarth Press, 1951), esp. pp. 50–51; S. Freud, "The acquisition of power over fire," *Collected papers*, ed. by James Strachey (London: The Hogarth Press, 1950), **5**: 288–294; Karl Abraham, *Dreams and myths*, trans. by William A. White (New York: The Journal of Nervous and Mental Diseases Publishing Company, 1913); Ernest Jones, *Essays in applied psycho-analysis* (London & Vienna: The International Psycho-Analytical Press, 1920), esp. p. 286.

Franklin, who had presumed to draw down the lightning from the skies was often likened to Prometheus, as when the German philosopher Immanuel Kant called him "the modern Prometheus," or when Turgot penned his famous epigram, *Eripuit coelo fulmen* . . . , he snatched the lightning from the sky. I do not believe that either Kant or Turgot envisioned a Prometheus-like fate for Franklin. The "enlightenment" of the age enabled them to be somewhat free of the superstitions of the crowd. Indeed, Turgot concluded merely that the man who had braved the thunders of heaven need not fear the relatively impotent scepters of earthly tyrants, and the complete text of his epigram reads, *Eripuit coelo fulmen*, [*mox*] *sceptrumque tyrannis!*

As one might expect, the Abbé Nollet did not share in this general feeling of applause at man's willingness to stand up to the lightning. He was frightened at the possible consequences of such a dangerous act as interfering with lightning. Soon after the Marly experiments, he wrote of the anxiety aroused within him by the conduct of his fellow experimenters. It was no longer a joke. "By experiment after experiment," he wrote, "we have succeeded in touching the fire of heaven; but if through ignorance or temerity our profane hands abuse it, we would certainly have cause to repent; and what would we do if some grievous accident would cause us remorse, if consumed by unnecessary regrets, we were to bring into being the Prometheus of the fable and his vulture!"[101]

Nollet's fears seem to have been justified by the horrible death of Richmann one year later. Although Priestley referred, in jest, to the sentiments of the "magnanimous Mr. Boze, who with a truly philosophic heroism worthy of the renowned Empedocles, said he wished he might die by the electric shock, that the account of his death might furnish an article for the memoirs of the French Academy of Sciences," noting that "it is not given to every electrician to die the death of the justly envied Richmann,"[102] most of the printed discussion shows a sombre note. Morbid curiosity demanded information on every detail, and the printed accounts lay stress on the rapid decomposition of Richmann's corpse, and the frightful odor arising from it; a quick burial was, therefore, provided and no autopsy could be made.

We are told that the lightning may represent for man the punishing power of the father, and that man's fears of both are closely related.[103] This notion renders especially interesting a statement attributed to the Abbé Nollet, who, as we saw, dreaded the possibility of our realizing the myth of Prometheus; Nollet's statement reads that it is "as impious to ward off God's lightnings as for a child to resist the chastening rod of the father."[104] Today we would hardly call the child's resistance "impious"; in fact we would more likely ask: why should the child not "resist the chastening rod of the father"? In Franklin's willingness to rise above the superstition of his age, and particularly in the ease with which he ignored the possibility of a Prometheus-like fate and the wrath of the father's rod, we see him as an emancipated spirit and a herald of our modern age.

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[101] Nollet, *Lettres* (ref. 48, *supra*), pp. 17–18.

[102] Priestley, *History* (ref. 12, *supra*), vol. 1, pp. 107–108.

[103] Cf. Karl Abraham, *Selected papers*, trans. by Douglas Bryan & Alix Strachey (London: The Hogarth Press, 1927), p. 233, and the works listed in footnote 100, *supra*.

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[104] Quoted in Park Benjamin, *A history of electricity* (*The intellectual rise in electricity*) *from antiquity to the days of Benjamin Franklin* (New York: John Wiley & Sons, 1898), p. 592.

LIGHTNING PROTECTION SINCE FRANKLIN'S DAY

BY

K. B. McEACHRON[1]

LIGHTNING PROTECTION

Lightning protection began with Benjamin Franklin with the installation of the first lightning rod system in Philadelphia in 1753. Three years before, he had written to his friend Collinson in London proposing a method of protection of buildings and ships from lightning. He told of the similarities between lightning and electricity and described experiments showing how sharp points facilitated electrical discharge, and then he suggested the application of these ideas to the protection of buildings and ships in these words:

> If these things are so, may not the knowledge of this power of points be of use to mankind in preserving houses, churches, ships, etc., from lightning, by directing us to fix on the highest parts of these edifices upright rods of iron made sharp as a needle and gilt to prevent rusting, and from the foot of these rods a wire down the outside of the building into the ground or down the shrouds of a ship and down her side, till it reaches the water? Would not these pointed rods probably draw the electrical fire silently out of a cloud before it came nigh enough to strike and thereby secure us from that most sudden and terrible mischief?

In the years that followed, many lightning rod installations were made principally in America, England, France and Germany. There were successes and failures and questions arose about the grounding, the size and character of the conductor, joints, methods of attachment, and perhaps most controversial of all, whether the rods were to terminate in points or "blunts." Franklin's idea that sharp points could act so as to prevent a lightning discharge by neutralizing the charge of the cloud could be demonstrated successfully on a small scale with a static machine, but conditions of the actual lightning storm are not completely demonstrated by a static machine. Considering the distances between the point and actual cloud and the magnitude and rapidity of the build-up of charge in the cloud, the discharge from earth-points turns out to be too small to have any appreciable effect in preventing lightning discharges. However, Franklin was not unaware of the attractive effect, for in 1773 he wrote: "A house thus furnished will not be damaged by lightning, it being attracted by the points and passing through the metal without hurting anybody."

In 1882, 129 years after the first installation, a report on lightning rods was issued in London and New York by the Lightning Rod Conference which consisted of representatives of the Meteorological Society, Royal Institute of British Architects, the Society of Telegraph Engineers and Electricians and the Physical Society. The following conclusions were reached by the Conference which were, of course, based on the knowledge of that day. In some instances, comparisons are made with the 1951 ASA Code C.5.

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[1] General Electric Company, Pittsfield, Mass.

Points—Bevel air terminal at top to receive direct stroke without damage—arrange points a foot below top to allow silent discharge.

Material—Since iron has the disadvantage of joints due to short lengths and low resistance to corrosion "We think that in all ordinary cases a copper rod will in the end prove to be the cheapest, as it will certainly be the most durable."

Size—Suggested Weights (oz./foot) of Lightning Conductors

Material	Conference of 1882	ASA Code C.5 (1951)
Copper	6 to 7	3
Iron	35	5.1
Aluminum	Not available until 1886	1.5

Shape—It was agreed that the configuration of the conductor was of no particular importance and in this connection it is to be noted that the ASA Code C.5 specifies the weight of copper to be 187.5 pounds per 1000 feet whether the conductor be in the form of cable, tubing, solid section or copper-clad steel. Minimum diameter of wires and thickness of ribbon or wall of tube is specified. Evidently the configuration of the conductor bears no relation to cross-section.

Joints—are to be kept to minimum and soldered.

Attachment to Buildings—"The evidence against the use of glass or other material is overwhelming and insulation may be regarded as unnecessary and mischievous. The essentials are, (1) that the rod be attached to the building by fastenings of the same metal as itself, (2) that the fastenings be of adequate strength, (3) that they be of such a form as not to compress or distort the rod, (4) that they allow for its expansion and contraction," (5) that they be properly attached.

Earth Plates—"This portion of the lightning conductor is of utmost importance, but has hitherto been most neglected.—A convenient earth connection is often afforded in towns by the iron mains for gas and water–we–state our opinion in favor of both. No connection should be made with soft metal pipes, because of the risk of their fusion and the conductor should be kept as far as possible from internal gas pipes on account of risk of lighting the gas at an imperfect joint."

The Conference also advised soldering to a plate of metal, copper to copper, or iron to iron, for if the same metals are not used galvanic action will set in (Galvani 1786 frogs legs). The plate may be flat or cylindrical, having a total surface not less than 18 sq. ft. and must be buried in a hole so deep that the surrounding earth "shall never be dry." The hole should be filled with coke or cinders.

Space Protected—The question of the space protected is one of very great practical importance, since it governs the number and height of the upper terminals required. It has been stated that the space protected was a cone having the point for its apex, and a base whose radius was equal to twice the height of the point. French (official) instructions dated 1875 suggest a base whose radius is 1.75 of its height. In England the base radius was assumed to equal the height of the point.

The method of determining the protection afforded as shown by Fig. 1 is the same as the method in use today.

The ASA Code C.5 under the heading, "Rods, Masts and Overhead Ground Wires," gives the following: "A radius of base equal to the height of the rod or mast in important cases, or up to twice the height in less important cases has been found to be satisfactory."

Height of Terminal—"This matter is one which may be left entirely to the option of the individual architects and engineers subject to the discussion under the heading of *Space Protected*." In France upper terminals as long as 33 feet were in use, whereas in England very short ones were in use. The ASA Code C.5 states: "The height of an elevation rod shall be such as to bring the tip not less than ten inches above the object to be protected." The ASA Code C.5 further points out that on flat surfaces the elevation rod should be longer but need not be longer than five feet. Furthermore, the spacing between air terminals, along ridges, parapets and edges of flat roofs shall not exceed 25 feet.

Internal and External Masses of Metal—Such masses are to be connected to the earth or the lightning conductor, but large meters inserted in pipes should always be by-passed electrically. The ASA Code C.5 states that metal situated wholly within the building which, at any point comes within six feet of a lightning conductor, should be bonded to it and if of considerable size or extent, should be grounded at its furthermost extremity. In general, it is better where water pipes are not available to avoid the necessity of interconnection by keeping conductors more than six feet away.

The foregoing statements and comparisons are made largely for the purpose of showing that most of the general principles as practiced today were well known in 1882, only six years after Edison developed the incandescent lamp.

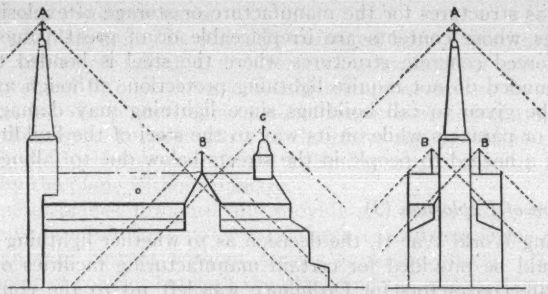

FIG. 1. Use of cones of protection as illustrated in the report of the Lightning Rod Conference, London, 1882; p. 13.

In the years which have elapsed, many installations of lightning rods have been made. Frequently, they were sold by unscrupulous salesmen, improperly installed or poorly maintained with the result in some quarters that the lightning rod fell into disrepute. Today the lightning rod, partly at least because of the Code, is regarded as a system with a good record, not perfect, but having probably prevented at least 90 per cent of the fires that would have otherwise occurred.

Statistics are missing in most localities but in the State of Iowa, Professor Geise (**1**)[2] has given the following figures for the years 1930 through 1950. Lightning damage of $3,529,670 occurred in a total of 1429 buildings during the twenty-year period. 122 of these buildings were equipped with lightning rods while 1307 were unrodded. The data are for "country" dwellings and barns and indicate that 91 per cent of the buildings damaged were unrodded. There is, of course, no record of those rodded buildings which were struck by lightning and which were not damaged. The true percentage for well designed and maintained systems would make a still better showing, since no doubt a considerable number of the rodded buildings were not in first class condition. In fact, test reports from the Farmers Mutual Reinsurance Company (2) of Iowa show that 50 per cent of 10,767 dwellings, and 58 per cent of 11,278 barns reported were rodded, but 15 per cent of 5416 dwellings and 44 per cent of 6442 barns were reported as defective. These samples may not be indicative for the entire state, but do give an indication of what the situation may be.

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[2] The boldface numbers in parentheses refer to the references appended to this paper.

Use of Lightning Rods

Lightning rods have found their greatest use in the protection of country homes and barns, but are used to protect valuable trees, chimneys, monuments, tanks containing flammable gases or liquids as well as structures for the manufacture or storage of explosives and buildings whose contents are irreplaceable or of great value. Steel or reinforced concrete structures where the steel is bonded together and grounded do not require lightning protection, although attention should be given to tall buildings since lightning may damage stone copings or parapets while on its way to the steel of the building, thus creating a hazard to people in the streets below due to falling debris.

Protection of Explosives (3)

During World War II, the decision as to whether lightning protection would be provided for certain manufacturing facilities operated by private contractors for Ordinance was left up to the contractor. Records show that from 1943 to 1946 the unprotected Indiana Ordinance Works lost approximately 500,000 pounds of explosives; an explosives magazine, a shipping house and operating building, and other damage exceeded $100,000 as the result of six lightning strikes. In contrast, the immediately adjacent protected Hoosier Ordinance Plant reported no losses from lightning.

A survey by Ordinance of the lightning experience for the period 1944 through 1948 shows the following:

a. Protected structures were struck 330 times; damage negligible.
b. Unprotected structures were struck 52 times; damage exceeded $130,000.

The character of the lightning protection used will depend upon what is to be accomplished. Conducting masts properly grounded will protect in practically every case objects within a cone whose base radius is equal to its height, from being struck by lightning. To prevent induced voltages from appearing between conducting objects within such a cone, it becomes necessary to use a Faraday cage; the more complete the cage the more certain will be the proper control of induced voltages. It is, of course, desirable to interconnect and ground effectively all large masses of metal inside the structure or area. A reinforced concrete structure with the reinforcing bonded and grounded, or a modern steel building, are examples of this sort. An all-metal automobile is an example of the Faraday cage. Persons inside are safe from lightning as long as they are completely inside, but secondary effects could be troublesome, such as temporary blindness resulting from a brilliant flash close by.

Protection of Airplanes

Lightning does strike airplanes in flight, the path being often between wing tips or from nose to tail. Antennae have been struck and eliminated, particularly the trailing type. Planes have been lost during lightning storms but it is not yet a matter of certainty that lightning was the direct cause.

Wooden planes may be seriously damaged from a structural point of view, and when taking the extreme turbulence often present in a lightning storm into account, it would seem wise not to fly through such storms. To protect such a plane requires means of preventing voltage differences between parts of the plane and providing paths of sufficient conductivity so that the lightning stroke current may be carried by the plane without damage.

All-metal planes automatically provide a Faraday cage which can be effective in minimizing potential differences and enable the plane to carry lightning current without serious explosive effects. However, at the point of contact between the plane and the stroke, damage may result from pressure effects or from burning metal parts such that structural weakness may develop. Current passing through propeller bearings may cause roughness and eventual trouble, or may freeze ball bearings or roughen them so that operation of control surfaces would be difficult if not impossible; bonding has been used to minimize such difficulties. Entrance of damaging discharges from strokes involving the antenna has resulted in fires and failure of communication equipment which in itself may be serious. This hazard can be reduced through the use of suitable arresters and more care in the disposition of inflammable material.

Pilots have been blinded for several seconds or even minutes by the intensity of the lightning strokes making contact with the plane, but a few feet in front of them. Planes have been off course because of loss of accuracy of the magnetic compass through the magnetization of ferrous parts of the plane, due to strokes to the plane. Many of these effects can be minimized but the lightning storm remains a hazard to be reckoned with, although the accompanying turbulence is probably a greater hazard than the lightning itself.

Protection of Television and FM Antennas

In view of the widespread use of television and FM outdoor antennas and the uncertainity of users as to the proper method of lightning protection statements based on a recent article by Smith (4), NFPA engineer, may be helpful. He states:

> The installation requirements of the Underwriters' Laboratories standards for master labeled lightning protection systems require that masts, if of metal, when installed on the outside of the building shall be bonded to the lightning protection system with standard lightning conductors or the equivalent.

As to the grounds, he points out that the National Electrical Code permits the bonding together of several electrodes, such as those used for grounding the lighting system, communication systems and the lightning protection equipment.

Mr. Smith further states:

> A lightning arrester of the type intended for the television or FM antennas should be installed at the point where the ribbon lead-in wire enters the building. The coaxial type of a lead-in wire does not require an arrester if the sheath conductor is grounded. The ground wire from the arrester should also be connected to approved ground electrodes. Indoor antennas do not require grounding or arrester protection but both antenna and lead-in wires as well as lead-in wires from outdoor installations should be spaced at least two inches from other wiring, except where the other wiring is in metal armor or pipe.

Care should be taken to be sure that antennas cannot fall on power wires in the event of failure of the structure due to any cause such as sleet or wind. Support on chimneys is not recommended. Mr. Smith's article should be consulted for further details.

Protection of Ships

Although not so necessary today, because of the advent of steel hulls and masts about 1880, yet for the record it seems important to discuss briefly the magnitude of the lightning hazard to wooden ships. Quoting from a book published in London in 1843 by Sir W. S. Harris (5), the following is found in the introduction:

> In the British Navy the effects of lightning have been most disastrous. Since the commencement of the war in 1793, more than two hundred and fifty ships are known to have suffered in thunderstorms. . . . In one hundred and fifty cases, the majority of which occurred between the years 1799 and 1815, nearly one hundred masts of line-of-battle ships and frigates, with a corresponding number of top masts and smaller spars, together with various stores, were wholly or partially destroyed.

The lightning conductor first applied to ships made use of chains or links of iron or copper extending in many cases from the top of the highest mast over the side of the ship into the water. Such a system was found to be objectionable and was abandoned, being replaced in many cases by a system developed by Sir William Snow Harris which provided a continuous path between the top of the masts and the keel of the ship. The system where used was reported to be very satisfactory. It was first suggested in 1821 to the British Admiralty and was later adopted by the navies and merchant services of most countries.

The ASA Code C.5 states that the ground of radio antennas constitutes sufficient protection for vessels of other than steel construction except where wooden masts or spars are employed, in which case all metal fittings such as trucks and bands are to be permanently and effectively grounded. The Code should be consulted for more detailed information.

The Lightning Stroke

As the result of lightning investigations over the last 25 years, lightning strokes are known to generally consist of continuing current with superimposed current peaks. The continuing current may be of the order of 250 amperes or more and may last as long as 1.6 seconds. Such a current flow will cause thermal effects which will melt conductors if too small, and may cause fires or explosions if direct contact is made to sheet metal surfaces thin enough so that holes are burned through, and molten metal or sparks cause inflammable material underneath to ignite. Lightning strokes to ordinary terrain are initiated with a current peak and may be followed by a succession of current peaks of differing magnitudes, usually called multiple strokes. These current peaks may reach their crest in a time of 1 microsecond, have a crest value of thousands of amperes, and on the average will reduce to one-half crest current in a time of the order of 40 to 50 microseconds. The current peaks represent most of the hazard to electrical systems and are responsible for the thunder and the explosive effects of the lightning stroke.

Usually lightning strokes contain both continuing current and current peaks, although strokes to extremely tall structures may not contain any current peaks. Such a lightning stroke does not produce the usual thunder.

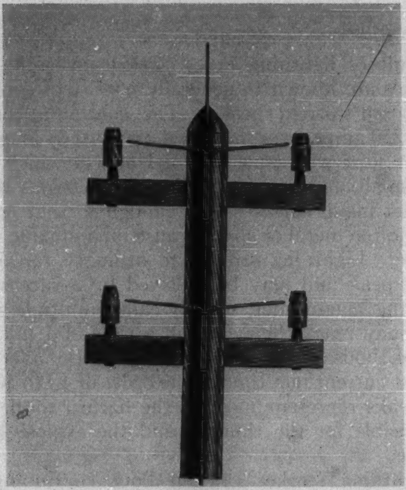
COMMUNICATION SYSTEMS

Protection of Communications Systems

In general, apparatus connected to conductors exposed to the effects of lightning will require protection to reduce or substantially eliminate the possibility of damage or failure which would result in an interruption to service. Much of such apparatus involves coils of insulated wire associated with cores of steel with supporting structures and enclosures which are connected to earth for reasons of safety to personnel. The wires usually are insulated from each other by a covering of enamel or some form of cellulosic material, and similarly from the magnetic core with some sort of solid insulation. In general, insulation between live parts and grounded parts consists of air in combination with solid insulation, as for instance in cable where the paper covering acts as a separator, the dielectric strength being supplied mainly by the air.

Telegraph Systems

Communication apparatus usually operates at a relatively low voltage and insulation levels are therefore generally low, so that induced voltages as well as direct strikes have been a serious source of trouble.



Taken from "A Practical Treatise on Lightning Protection," by H. W. Spang, Philadelphia, 1877.

FIG. 2. Protection of wood poles carrying telegraph circuits through the use of the lightning rod and associated conductors to prevent pole splitting and limit the voltage on line conductors.

Spang,[3] a telegraph engineer, writing in 1877 (6), thirty-three years after Professor S. F. B. Morse established the first commercial telegraph line between Washington and Baltimore, states:

> The telegraph poles and wires are especially liable to be struck by lightning discharges, being extended over a large section of territory.
>
> When a thunder cloud is above or within about five thousand feet of an overground or underground telegraph line, in which the earth forms part of the circuit, it causes by induction, the natural electricity of the line to be decomposed, the electricity of the same phase as that contained in the cloud being driven along the line in the form of a current to the earth over the

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[3] Spang is quoted here, not because he is necessarily the best authority, but rather because he has given a brief and concise presentation of the contemporary practice and thinking of that day.

> metallic terminals at the ends of the line, while the portion of the line nearest to the cloud is highly oppositely electrified. Every time a discharge takes place towards a neighboring cloud or to the earth, the disturbed electrical equilibrium is restored, producing a current which generally flows in the opposite direction to that of the battery current, and momentarily neutralizing the latter current. These reversed currents sometimes happen so frequently as to greatly interfere with, or altogether prevent, the working of the line, and they also cause wrong signals to be given by electric signaling apparatus and wrong time by clocks which are operated by ordinary electro-magnets.

Apart from the loss of instruments, difficulties were experienced in telegraph stations, particularly when storms were near and violent because of sparks jumping from one object to another sometimes many yards apart. Heavy lightning near telegraph lines resulted ofttimes in melted conductors, destruction of poles and apparatus, and even stations in some cases. One method used in those days to reduce these troubles is illustrated in Fig. 2. A ground-wire was attached to every fourth pole with staples, and extended above the top of the pole about 4 inches being grounded through the use of a coil of wire buried below the base of the pole. Side conductors extended along the cross-arms to within one inch of each telegraph line.

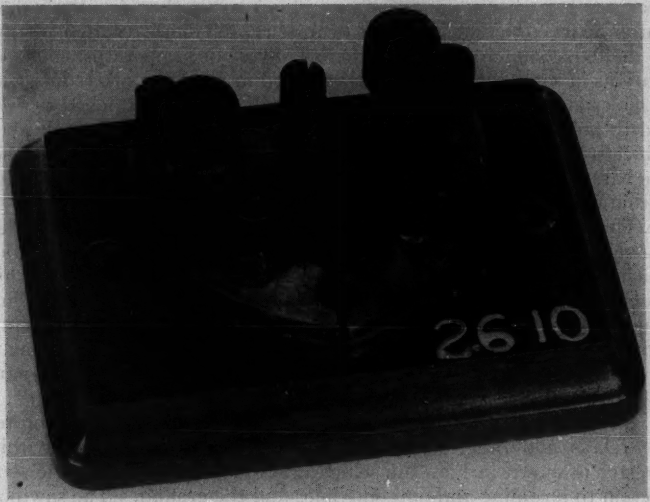
This type of line protection should have, and no doubt did, reduce damage to poles and cross-arms, and limited the discharge which could reach office equipment, and perhaps indicated a line of thinking which prepared the way for the overhead ground wire for the power lines which had not yet been developed, except for arc lamps which were in limited use for street lighting. At this time Edison was trying to develop the incandescent lamp, and Gramme had invented the dynamo only seven years before.

In the telegraph offices lightning arresters were installed to protect the relays and other equipment. One form of telegraph lightning arrester is shown in Fig. 3 in which brass plates are provided for connection to incoming and outgoing lines and the ground. The sawtooth type of gap electrode is clearly visible in this photograph. In such protectors provision was made for grounding the circuits through the insertion of a plug or cutting out the local instruments as desired. This same protector is also shown in T. D. Lockwood's book entitled "Electricity, Magnetism and Electric Telegraphy," (1883).

The protection of underground cable connected to overhead line was accomplished by means of a lightning arrester connected to the entering wire at either end of the cable and a coil of fine insulated copper wire connected between the arrester and the end of the cable wire, so that for heavy discharges the wire would act as a fuse and protect the cable.

In the succeeding years, a choke coil type of arrester was developed, the Argus arrester of this type being for many years standard with both the Western Union Company and the Signal Corps. Magnetic devices which were modifications of the Reid arrester developed in

1846, were in use as were thermal arresters which grounded the line when the lightning current expanded a wire connected to the telegraph line. Because of the lowered dielectric strength of air at reduced pressures so-called vacuum arresters found some application. The Brach arrester using carborundum was in use during the early 1900's. This material is used extensively in power arresters today. Carbon blocks separated by mica spacers began to come into use in this period and have continued until the present time, with modifications and improvements.



Courtesy of Western Union Telegraph Company.

Fig. 3. Type of lightning arrester used by telegraph companies, superseded more than sixty years ago.

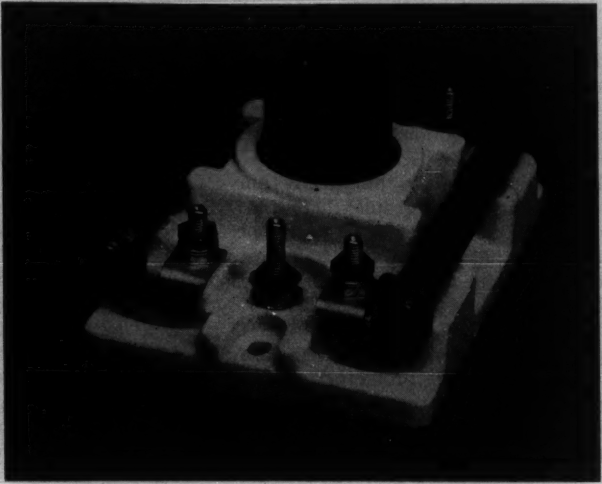
As the number of telegraph circuits increased and metallic circuits replaced one wire grounded circuits, arresters of necessity became smaller and were installed in groups. Fuses became a part of the general protection scheme when power lines began to cross or parallel telegraph lines.

Lightning interference to telegraph service over grounded circuits has been materially reduced due to improvements in apparatus, protective devices, methods of application and improved grounding practices. Metallic circuits which are growing in telegraph service, are less subject to lightning interference and service over them can be made largely immune to lightning by such means as drainage systems employing accurately balanced coils, the center tap being grounded.

Telephone Apparatus

The telephone was developed by Bell in 1876. The problems of protection of the apparatus from the effects of lightning were similar to those of the telegraph which had been in operation for over thirty years. Naturally, the same types of protectors were used for the telephone which were currently in use with the telegraph.

By 1900 the carbon block type with fuses was in common use for both telegraph and telephone. In operation, a lightning discharge passes to ground through the small air gap allowed by the mica spacer, holding the voltage sufficiently low so that the associated apparatus is not damaged. The potential of higher voltage power lines is in general high enough in the event of a cross-up to jump the carbon gap, and in this case the flow of power current is sufficient in most cases to blow the fuse and isolate the apparatus from the incoming line to which it was connected. Occasionally the fuses may blow as a result of lightning. Larger fuses would reduce the number of such blowings, but would also reduce the protection against the flow of power current.



Courtesy Bell Telephone Company.

FIG. 4. Protector block with fuses as used by the Bell Telephone System.

Improvements have been made in these protectors but the fundamental principle has remained the same down to the present time. Such a carbon-mica-gap has a very small time-lag with fast rates of voltage rise which made them well adapted to the job they had to perform. In Fig. 4 is shown a phantom view of such a protector as used by the Bell System wherever open wires enter a subscriber's station. Similar protectors, but without fuses, are used where overhead open wires enter cable or in central stations. As a general practice cable sheaths are tied to the earth and to the protector ground.

Today pole protection is not provided for suburban or rural circuits by the use of lightning rods on poles. However, on long toll lines there is a growing use of a down-wire extending above the pole and terminating with a gap at the lower end. This construction prevents pole shattering as the result of direct strokes but avoids the possibility of grounding the telephone circuits. Overhead cable and messenger wire are both grounded. In some cases underground cable may have a guard wire located close to the cable to reduce lightning currents which might flow through the cable, thereby reducing the potential difference between conductors within the cable and its sheath. The possibility of holes being burned through the cable sheath is also reduced by this method of protection. Stronger conductor insulations are being considered using new materials now available, which may make arrester protection of cable less necessary.

Protection for subscribers' stations where overhead exposure of conductors is present is practically universal in the United States. Both telephone and telegraph practice has been to rely on the protection provided, and design the apparatus to operate with a reasonable margin of safety. It has been stated that the telephone plant in the United States has a value of about ten billion dollars and that approximately one-half of this investment is influenced by the protection afforded by lightning arresters. Such data are not available for the telegraph companies, but like telephone practice, reliance based on long experience is placed on the protector used and the apparatus designed to coordinate with the protection. Since the character of the telegraph business is so different in relation to exposure and individual use of equipment compared to the telephone, it seems probable the percentage of investment requiring protection would be much less, perhaps of the order of one-half that given for the telephone plant.

Thus the protective system of Franklin with its appropriate modifications has had a profound effect in improving the reliability and reducing the cost of operation of communication systems.

Suitable protection is also required for radio and television transmission facilities and codes for protecting receiving equipment and structures in which they are located either have been prepared or are under study.

PROTECTION OF POWER SYSTEMS FROM THE EFFECTS OF LIGHTNING

Although exact data are not available, it is known that a high percentage of system transmission 115 Kv and above is protected by one or more overhead ground wires. It is estimated that at least 80 per cent of station apparatus is protected by lightning arresters or gaps.

For systems operating at voltages less than 115 Kv the overhead ground wire is decreasingly used, since it becomes less effective as the insulation strength between lines and ground becomes less with decreasing system voltages. Apparatus connected to such lines is generally protected by lightning arresters.

The methods of protection now in use for power apparatus are a direct outgrowth of the work first done by Franklin in establishing the lightning rod, and second by the telegraph companies in developing gap methods of protection. The telephone and power companies both had their beginnings in the 1870's but, while telephone practice could follow that of the telegraph which had been in operation for 30 years, power systems, because of the relatively high voltage and heavy currents, could not use simple gaps without a service interruption.

The Overhead Ground Wire

The problem of protecting a transmission overhead wire system is to prevent a flashover of the insulation either between line conductors or between line and ground. Since most high voltage systems now operate with the system neutral grounded, a conducting path between line and ground would allow power current to follow, frequently resulting in circuit-breaker operation and often an interruption to service. Thus the problem is to prevent the flashover of such insulation, either in the span between supports where the insulation is air or at the supports where the insulation is either glass or porcelain alone or in combination with wood as in a wood cross-arm or pole.

It also is desirable to keep the voltage between conductors and ground as low as economically possible, since a traveling wave will move from the point struck to the ends of the line with less stress if less voltage is allowed at the point struck. It is to be remembered that induced voltages due to lightning will be of little importance on systems 115 Kv and above as it is probable that such induced potentials seldom reach values as high as 600 Kv. In general, then, the higher voltage systems will have to protect only against direct strokes, while the lower voltage systems will have both induced and direct strokes to take into account.

With the knowledge of lightning now available, it can be stated that properly located ground wires, with down wires at proper distances apart with ground resistances and insulation at the supporting structures in proper relation and with balanced clearances between conductors and grounded wires, lightning flashovers can be controlled to any desired degree. How this has come about can perhaps best be understood by tracing the development of the ground wire since its beginning.

The earliest usage of the overhead ground wire appears rather uncertain. Lockwood (7) in 1892 stated that in order to improve protection of telegraph lines Reid had "put a lightning rod on each pole, and run this wire from pole to pole, grounding it where necessary on the pole rods." Whether or not this was expected to do more than reduce the induced voltages was not stated. Such construction would reduce pole shattering.

As to the first use on power systems, Stanley (8) at an A.I.E.E. meeting in 1894 said that,

> In 1885 or 1886 I built an alternating line, and found I had to protect it from lightning; so instead of putting my wires underground, I put my ground over the wires, and strung a ground above my line, grounding it every pole or two; and obtained very satisfactory results.

At the same time Wurts (9) reported that a Staten Island plant had good results with the overhead ground wire while at Telluride in Colorado the results were not satisfactory. With further reference to the installation at Telluride, Mr. Wurts said,

> The overhead ground wire at Telluride, as I remember it, was suspended three feet above the circuits to be protected. The circuits were run on either side of a single cross-arm and the ground wire was grounded at every other pole. The lengths of the circuits ranged from three to ten miles. The overhead wire was of course not connected to ground plates, which would be impracticable in a case of this kind, but ground connection was made by means of a bare galvanized iron wire run down the pole and then forced into the earth as far as possible. This was the method adopted by the system I referred to on Staten Island.

In the light of present-day knowledge, such a system might be of considerable help in reducing induced potentials, but would hardly do more than protect the pole on which the down wire was located in the event of a direct stroke of average magnitude. The thinking of the time was well expressed by Steinmetz (10) when he commented at the same meeting, speaking of the direct stroke to the circuit or to the power station that,

> I am glad to agree with Mr. Wurts that this is a very infrequent phenomena. I am inclined to think, however, that if it takes place, it matters little whether you are protected by lightning arrester or not; the only thing you can do is to trust in Providence and repair what is left of the station.

In 1907, 13 years later, Creighton (11) observed that insulated wires inside metallic sheaths, whether underground or overhead are protected from the static charge of cloud lightning. He said because of expense such a practice is often uneconomical.

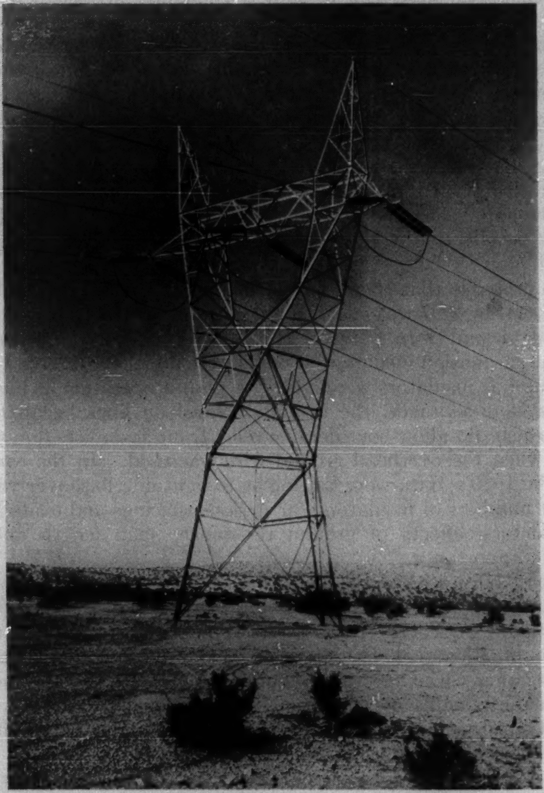
> The next best thing is to put the ground over the line wire. The further above the line wire the grounded wire is placed the better the protection. Dr. Steinmetz recommends that an overhead ground wire be so placed that two imaginary lines drawn from this wire 45 degrees from the horizontal will include all the line wires between them. Each additional ground wire, properly placed, gives some additional protection against induced static electricity from the clouds.

Creighton further notes that the overhead ground wire acts to protect wood poles from shattering from direct strokes, and has the possibility of carrying direct strokes past the insulators without shattering, and indicates the need for more data on this point.

Mershon (12) described in 1907 a triangular arrangement of conductors on the system of the Niagara, Lockport and Ontario Power Company in which the uppermost conductor was spaced 6 inches away from a grounded wire or horn extending above the top of the tower. This same method was tried again some 30 years later on a 26 Kv wood pole line by the Public Service Company of New Jersey (13) except that the gap was inside a fiber tube so arranged as to interrupt power follow current. By these means the top conductor could act as a ground wire momentarily when the potential due to lightning was high enough to spark the gap. This method has been used to a very limited extent, since to be effective against direct strokes high insulation levels are required.

It is probable that the development of the suspension insulator by Hewlett (14) in 1907 was one of the important factors in permitting the overhead ground wire to give a satisfactory account of itself. By using the suspension insulator, systems were no longer limited to 69 Kv or less, and as insulators were added to permit operation at higher and higher system voltages, the insulation level on lines began to reach values which did allow considerable relief from flashovers due to direct strokes when the overhead ground wire was used. In the early days before the 1920's, data were lacking as to lightning flashover values for different numbers of insulators, for various spacings and configurations of conductors, effects of ground resistance, span length and other factors of importance.

In the laboratories of the General Electric Company and the Westinghouse Company studies were being made designed to supply such information. Peek (15) in a series of papers before the American Institute of Electrical Engineers supplied much fundamental data which together with the work of Fortescue (16), Ryan, (17) and many others made possible an intelligent approach to the problem. However, laboratory data alone could not solve this problem without a knowledge of lightning as to possible magnitudes in terms of current and time and the frequency of occurrence. In the ten year period beginning 1926, both General Electric and Westinghouse together with several power companies, notably operating units of the American Gas & Electric Company and the Electric Bond & Share Company, set up cooperative investigations to secure field data. Most of the work was done on systems 115 Kv to and including 220 Kv. The purpose was to study the performance of the lines, overhead ground wires, insulators, steel tower and wood pole structures, and various methods of grounding. Measurements were made at a sufficient number of points so that statistical data might be obtained to indicate frequency of occurrence as this factor is necessary in order to determine the economics of various methods designed to protect against any assumed set of conditions.



Courtesy Bureau of Power & Light, Los Angeles, with permission of Random House, Inc., publisher of "Playing with Lightning."

FIG. 5. Strain tower of the Hoover Dam-Los Angeles 287 Kv line of the City of Los Angeles. Note two overhead ground wires at top of structure.

This work carried on simultaneously with the laboratory investigations yielded sufficient information so that in 1936 the 287 Kv double circuit line from Hoover Dam to Los Angeles (Fig. 5) could be so built that only three interruptions which might have been due to lightning occurred during the first 13 years of operation. The value of the buried counterpoise had been demonstrated in the field investigations carried on previously with the result that two buried counterpoises were provided for each of the two tower lines. The conductors are supported on 24 insulators in suspension. The investigations made have indicated that as a rough approximation a line supported by sixteen $5\frac{3}{4}$-inch spaced insulators with properly located overhead ground wire or wires and ground resistance of 10 ohms or less should be practically immune from lightning.

The counterpoise is used as a substitute for a low resistance ground; it may be continuous between tower footings or may consist of a hundred or more feet of buried conductor extending out from tower footing in any suitable direction. In 1907 Steinmetz (18) said that E. J. Berg had proposed some years before to run a shallow ditch along the line and run an underground wire in the ditch connected up with the overhead ground wire using the buried wire as an energy dissipating wire. Artificial grounds had been used in connection with broadcasting towers prior to their investigation and use in the 1920's for power line tower grounding.

Today the protection of outdoor stations from direct strokes of lightning is accomplished through the use of an extension of the overhead ground wires on the incoming lines over the station structure with enough clearance to prevent side flashing to station conductors or apparatus. Masts acting as lightning rods are also frequently used in lieu of overhead ground wires, due consideration being given to cones of protection.

Insulation strength is often built to a higher level economically by the use of wood arms of such length and conductor spacing that the impulse strength of the porcelain insulators in series with the wood is sufficient so that the overhead ground wire can offer a reasonable degree of direct stroke protection with ground resistances which are reasonably attainable. In such a case pole and cross arm gaps may be used to keep the lightning discharge from passing through the wood and causing it to shatter. Gapped wood strain insulation used in guys helps to maintain a protectable impulse strength to ground.

Economic Aspect

It is difficult to determine the value of the overhead ground wire, but it is certain that its proper use has resulted in satisfactory improvement in the operation of transmission circuits. Not all of the improvement has come from the lightning protection alone; such developments as the high speed circuit breaker, interconnection of systems, proper relaying, and parallel operation have all helped to make lines more reliable. The overhead ground wire has changed a situation which in the first 20 years of this century seemed to be a problem on which little progress was being made.

The lightning rod of Franklin with its connection to ground and cone of protection has become an overhead ground wire with its tent or wedge of protection and is in successful use where there is lightning and its use is justified, protecting the service of electric light and power companies whose investment in the United States alone at the end of 1950 exceeded 21 billions of dollars.

THE LIGHTNING ARRESTER FOR POWER CIRCUITS

The lightning arrester for power circuits is essentially a device which under normal system voltage allows little or no power current to flow, but which is capable of allowing large volumes of current to flow when required to conduct lightning currents to ground without allowing a sufficient rise in potential to endanger associated apparatus and yet restores itself to substantially its original condition without interfering with the continuity of service.

In order to apply lightning arresters efficiently, the impulse strength of the apparatus to be protected must be known for any form of lightning disturbance which might occur on electrical circuits. Obviously to be able to test the lightning arrester and the apparatus connected to the same circuit it was necessary that the wave shape and magnitude of lightning strokes be determined, as well as the frequency of their occurrence. Through the use of the Klydonograph in 1924 (19) and the surge voltage recorder in 1927 (20) making use of calibrated Lichtenberg figures as a measuring means, it became possible to determine polarity and impulse potential with reasonable accuracy. By this time it had become quite certain that lightning did not oscillate, but reflections in electrical circuits could take place which would make Lichtenberg figures difficult to interpret. Using these devices with suitable electrostatic coupling to transmission lines, valuable data were obtained relating to flashover values of insulators, attenuation, polarity and frequency of occurrence. At the same time these field results were being correlated with data from the high voltage laboratory where the wave shape of the applied impulse could be controlled. The successful application of the cathode ray oscillograph (21), in 1925, to the measurement of single transients made possible much information which up to this time could only be obtained through tedious and sometimes doubtful measurements using the needle or sphere gap with little or no knowledge of wave shape which had a profound effect upon the accuracy and interpretation of results.

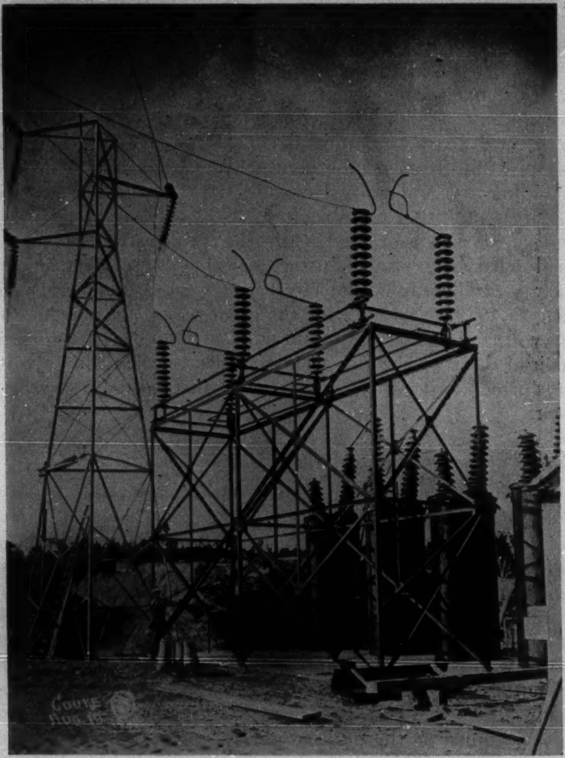
An additional forward step was taken in 1932 with the development of the magnetic link (22), which in use resulted in a magnetized packet of steel whose subsequent calibration gave a reasonably good indication of the amount of current and polarity which passed through the conductor, be it ground wire or tower leg associated with the magnetic link. These data were not limited by flashover voltage of the insulation as in the case with the Lichtenburg figures, but could give directly the amount of current flowing in the stroke of lightning providing the current in all the parallel paths was measured at the same time. Many data from utilities, notably Pennsylvania Power & Light and American Gas & Electric, together with foreign sources, became available using the magnetic link from which reasonably good values were obtained as to crest currents in tower legs and in the direct stroke and the frequency of occurrence.

Cathode ray oscillographs coupled to transmission lines were in use for several years beginning in 1929 (**23**) and additional data on wave shape came from a nine year study of lightning to the Empire State building (**24**) and from strokes to the Cathedral of Learning (**25**) in Pittsburgh and other tall structures.

These field data obtained with the cooperation of the utilities combined with field studies using portable impulse generators and cathode ray oscillographs (**26**) covering a period of several years also beginning in 1929, together with the great wealth of information from the high voltage laboratories (**27**), finally made it possible to secure the fundamental data with which to coordinate the lightning arrester and the transformer and other apparatus connected to overhead power conductors.

Development of the Lightning Arrester

The first important development in power arresters came as a result of the discovery by Wurts (**28**) in 1892 of the so-called non-arcing metals. In use the most important of these was brass, the copper being alloyed with zinc, which Wurts found had the property of suppressing an alternating current arc if the current applied potential were suitably limited as to magnitude. In 1894 (**29**) he described an arrester as being in successful operation rated 1000 volts which consisted of seven non-arcing brass cylinders $\frac{1}{16}$ inch apart connected between lines. The fourth cylinder was connected to the ground thus interposing 3 gaps between each line and ground. By 1907 arresters of this type known as the multigap arrester were in extensive use for voltage ratings up to 30 Kv. Such arresters consisted of a large number of spark gaps in series, arranged with various shunting resistances so that for weak disturbances a considerable resistance was left in the circuit, while for heavy discharges a short circuit to ground existed allowing free flow of current to the earth. This permitted a power short, but the non-arcing metal gaps were designed to allow but one-half cycle of power current to follow. The operation of such an arrester which short-circuits the system could not handle recurrent discharges because of the heating effect on the gaps, and the volume of the short-circuit current which the gaps could seal was also a limiting factor. These arresters gave a good account of themselves, but an arrester which did not short the system was needed, as systems grew and short-circuit currents increased. Such an arrester might be like a safety valve, in that no current would flow until a certain level of potential was reached, and then for higher potentials the resistance to flow would become very small. When the voltage dropped to a prescribed low level the arrester characteristic would be such that it would limit the system current to a sufficiently low level that the arrester itself would be able to quickly stop the flow of this small power current.



Courtesy General Electric Company.

FIG. 6. 140,000 volt outdoor type aluminum lightning arresters. Cooke Development Ausable Electric Company, Michigan.

The Aluminum Arrester

In 1857 Buff discovered that an aluminum electrode immersed in an electrolyte allowed a free flow of current in one direction, but opposed the flow of current in the opposite direction. This arrangement was used by Ducretet in 1875 as a rectifier.

The use of the aluminum-electrolyte cell in a lightning arrester was first patented by Ferranti in England in 1901. He used aluminum trays filled with electrolyte in series with a gap for use with alternating current application. He also used the aluminum arrester to prevent flashovers on d-c. generators.

In this country both Westinghouse and General Electric took up the development of aluminum arresters in the period 1904 to 1906. The aluminum cell consisting of two aluminum plates separated by suitable electrolyte, formed a film on the opposing aluminum surfaces whose thickness was dependent upon the magnitude of the alternating voltage. Thus the film automatically adjusts itself to allow only a very small current to flow. When excess potentials are applied the resistance is low momentarily, and thus the elements of the valve type arrester become available. In operation enough cells were placed in series so that the volts per cell were of the order of 300. Such an arrester had quite a considerable capacitance, which was regarded as a valuable asset since Wurts had described in 1894 (29) a condenser being successfully used as an arrester in 500-volt d-c. circuits without series gap. The aluminum arrester was provided with a series horn gap when used on a-c. circuits which was shorted at specified intervals to maintain the film. The small system current allowed by the arrester was extinguished by the lengthening of the arc across the horn gap.

The aluminum arrester (Fig. 6) had wide acceptance, and was highly regarded as a protective device. Its maintenance with regard to film eventually became a serious problem, and the charging operation was looked upon with disfavor particularly when the use of radio began to be common. The aluminum arrester ceased to be manufactured about 1922 for alternating current use, but is still continued in limited manufacture for d-c. railway use.

The performance of the aluminum arrester was judged chiefly by its performance in service, since the needle gap and sphere gap were the only test means available for measuring extremely short time transient voltages, the cathode ray oscillograph not having yet become available.

Newer Forms of Arresters

The search for an arrester whose protective characteristics would be adequate and yet without the maintenance problems of the aluminum type culminated in the oxide film arrester described by Dr. Steinmetz (30) in 1918. This arrester patented by Crosby Field in 1917 consisted of cells, each composed of a porcelain ring containing PbO_2 between two metal plates spun over the outside edge of each ring. The inner face of each plate was coated with a varnish film, whose dielectric strength was such that at 325 volts per cell practically no system current would flow. When a suitably higher voltage was applied, such as would result from lightning, the varnish film would puncture and current flow through the PbO_2 with very little resistance. Since PbO_2 has the property of changing from a low resistance to a very high resistance (PbO) by the application of sufficient heat, the puncture in the varnish film would be sealed by a plug of PbO whose breakdown value was related to the system potential per cell. The oxide film arrester was provided with a single covered gap between hemispheres set to spark over at a value not much different from the system line to line potential. The oxide film arrester was in extensive use for approximately 15 years, being superseded by the Thyrite arrester in 1931.

The pellet arrester for use on distribution circuits was developed by Lougee (31) in 1921 and is still being manufactured. It consists of small pellets of PbO_2 coated with litharge (PbO) in series with one or more gaps and with varying lengths of pellet columns depending upon the arrester voltage rating. The pellet arrester has a very flat volt-time characteristic as shown by the cathode ray oscillograph, with very little system follow current.

In 1922 Atherton (32) described the auto-valve arrester, which consisted of a series of composition resistance discs about $\frac{1}{8}$ inch thick and 2 inches in diameter being separated from each other by mica ring spacers 3 to 5 mils thick. The distribution arrester used a single column of discs and the station arrester 4 columns in parallel all housed within a suitable porcelain container and supplied with a proper number of series gaps. As described by Slepian upon the application of overvoltage, discharge begins at the edge of the mica spacer and spreads over the surface as a glow.

In 1929 Slepian, Tanberg and Krause (33) discussed the discharge characteristics of fine pores of a naturally porous material, which led to the development of the porous block replacing the discs and spacers of the earlier auto-valve arrester. In 1937 Roman (34) described a new type auto-valve arrester with two gap structures, one called the quench gap and the other the switch gap. The quench gap structure consists of many closely spaced gaps with controlled voltage distribution whose purpose is to interrupt the flow of follow current at the end of the first half cycle of flow, while the switch gap connects the arrester in circuit using means designed to give a low impulse ratio. These arresters with minor modifications are in use today both in distribution and station arrester types.

Thyrite Arrester

The Thyrite (35) arrester development began in 1922 with the concept that the aluminum arrester, which had an excellent record as a protector, actually had consisted of two rectifiers connected in opposition in each cell. Since it was about this time that crystal rectifiers were being used as radio detectors, it seemed in order to try two carborundum crystals in series, and then discover a means for securing the multiplicity of parallel and series contacts with proper pressure so that the large volumes of current required could be carried without damage to the carborundum contacts. This was eventually accomplished with a volt-ampere characteristic such that each time the voltage was doubled the current increased approximately 12 times. Thus it became possible for the first time to calculate (36) the voltage permitted by an arrester while carrying lightning currents for any circuit arrangement commonly used. To complete the design of the arrester, however, it was necessary to design a new type of gap unit (37) which would have the over-all characteristic of very consistent and predictable gap breakdown built to interrupt the system follow current reliably and to be sure that its characteristics were permanent. This was accomplished with a sealed porcelain container having 9 gaps, each shunted by suitable resistance to maintain correct voltage distribution, each gap arranged so that the sparking over of one gap would irradiate the next. This gap arrangement with small modifications is still being supplied. Unit construction each of 11.5 Kv was introduced at this time. With more than 8 units in series a grading ring connected to the top arrester unit was used to assist in holding substantially uniform voltage distribution under rated voltage conditions. The Thyrite arrester of the construction described is being supplied at the present time, but with Thyrite having a flatter volt-ampere characteristic than was possible in the earlier designs, thus giving lower protective levels.

Line type arresters of both the Auto-valve and Thyrite types for application up to 69 Kv system voltage have been developed having a reduced current capacity compared to the so-called station type, but using substantially the same general principles in the design of the arrester. This is a lower cost insurance against apparatus failure, and is used where the station type is not justified by the value of the apparatus or service being protected.

Choke Coil

The choke coil as a protective means has been the subject of much discussion in the early years. In 1907 Steinmetz (38) indicated that the choke coil must be between the lightning arrester and the line. At the same time he noted that Creighton had found experimentally a point beyond the choke coil "where the voltage of the disturbance was greatly increased." It was further pointed out that the station wiring had electrostatic capacity and resonance might result with the inductance of the choke coil. The importance of keeping low values of station line capacitance and choke coil inductance was stressed.

By 1920 choke coils were in common use, usually in combination with lightning arresters. However, some operators used choke coils without arresters, in some cases using two in series.

By 1929 Jones and Hudson (39) from a mathematical analysis concluded that choke coils of inductances in common use were of doubtful value. The same year McEachron (40) presented a Cathode Ray Oscillograph Study using choke coils of usual inductance, in combination with lightning arresters and a five mile section of transmission line, which clearly showed that for impulses from a 400 Kv lightning generator sent over the line, the arrester voltage was nearly doubled at the transformer as a result of the resonant effect of the capacitance of the transformer and the inductance of the choke coil. This work sounded the death knell of the choke coil as an adjunct to a lightning arrester.

Distribution Arresters

Several designs of distribution arresters of the valve type are available from different manufacturers, the pellet and auto-valve already having been mentioned. The others in general make use of a column of carborundum crystals in a porcelain container with internal series gaps with ratings up to 15 Kv. The use of distribution arresters is widespread, and the duty severe, since insulation levels on the overhead wire circuits are often limited only by an occasional guy wire. The practice of grounding the primary neutral and interconnecting with secondary neutral and lightning arrester ground on the transformer pole is becoming pretty much standard practice. For rural lines primary neutral wires are often grounded every third or fourth pole, which considered with the grounds provided for secondary neutrals in customers' premises, give a very solid ground, which experience is showing results in fewer troubles during lightning storms. Early work in this area was done on the Toronto Hydro system and later at Minneapolis by Hood (41). Today such a solidly grounded system is tied in with station grounds, overhead ground wires, and telephone and lightning rod grounds. Thus we have not only good grounds but a multiplicity of grounds spread over a wide area in many cases, and the experience has been good.

Expulsion Arresters

Torok and Pittman (42) in 1931, when discussing a lightning investigation on a 110 Kv wood pole line in Arkansas, described the use of expulsion fuses rated 5 amperes and 75 Kv in series with a gap which they reported worked well as a protector, the gap protecting the wood and the fuse interrupting the power current. Later Pittman independently devised an expulsion arrester by inserting in either end of a 38-inch fiber tube copper wires so that a gap of 30 inches was left within

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the tube. This tube was then inserted between the insulator hardware and the connection to ground. Thus if the insulator flashed over, the supporting wood was protected and the power follow current extinguished by the expulsion action within the fiber tube. The expulsion protector tube, as it has been called, developed by both Westinghouse and General Electric, was used with a series gap to protect insulators on steel tower lines, and both insulators and wood in series on woodpole lines. Considerable experience was gained on 115 Kv and 138 Kv (**43**) circuits, indicating that the number of tripouts was reduced by a factor of from 40 to 90 per cent (**44**).

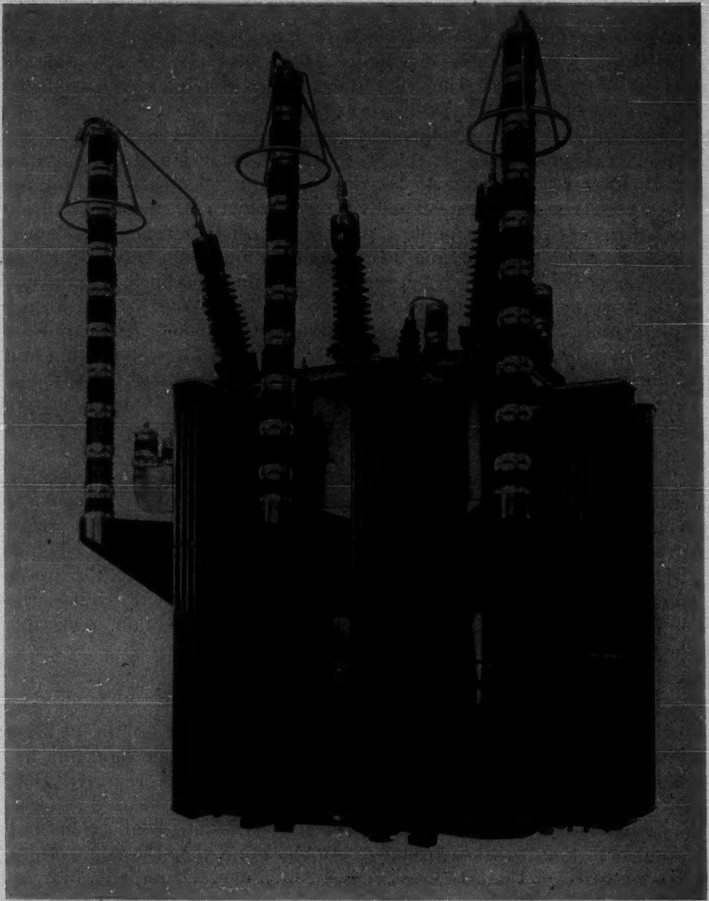
Expulsion protector tubes as they have been developed up to the present are not suitable for the protection of insulation of transformers except for voltage ratings 15 Kv and below, and for this use they are called expulsion arresters. The CSP transformer (**45**) uses an expulsion type arrester which is made a part of the distribution transformer. This construction has obvious advantages among which is compactness, and very short lead length between arrester and windings. Expulsion or valve type arresters are also arranged to mount on the transformer tank, or to be mounted separately on cross arm or pole. The expulsion protector tube when used on high voltage systems has a maximum and minimum current rating. When used to protect distribution transformers excessive erosion and consequently short life will take place under conditions of application where it is required to interrupt high short-circuit currents.

Tall structures several hundred feet in height, as at river crossings, may find difficulty in good protection against flashover of insulator strings, the ground being so far away that in the event of a direct stroke to the tower top the potential will continue to rise to flashover before a reflection from the nearest ground can begin to reduce the tower top potential. In such a case a protector tube directly across the insulator strings could operate successfully, its protection being unaffected by the distance to ground.

Basic Impulse Insulation Levels (BIL)

Summarizing in 1933 returns from a questionnaire to the utilities relating to installation and performance of high voltage lightning arresters, a joint sub-committee of AIEE and NEMA reported that lightning arresters were used almost universally, being located as close as possible to the equipment to be protected, with short connections and grounded to main station grounds. In the same year the transformer sub-committee of the AIEE Electrical Machinery Committee (**46**) reported that a satisfactory impulse wave shape for impulse tests on transformers would have a front of ½ to 2½ microseconds, and a tail reaching half of crest voltage in from 40 to 50 microseconds. Other data were given relating to how the test should be made.

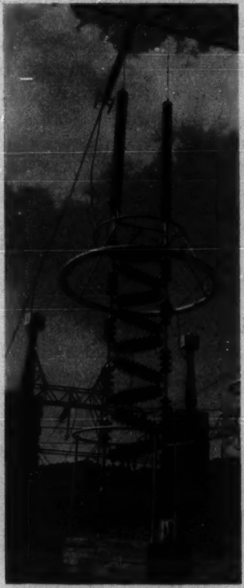
Standards for testing lightning arresters using specified wave shapes had been set up in 1928 and 1936, and protection levels which could be met had been published (1940) by the lightning arrester subcommittee for the industry. Thus the stage was pretty well set for



Courtesy General Electric Company.

Fig. 7. 138 Kv grounded neutral lightning arresters for protecting the high voltage winding of a power transformer of 15,000 Kva output, rated 139200GRY-69300GRY-4160 volts. Built for Indiana & Michigan Electric Company.

the AIEE-EEI-NEMA triple joint committee to set up Basic Impulse Insulation Levels in 1941. These BILs are the values of crest voltage ($1\frac{1}{2} \times 40$ microsecond full-wave) which apparatus such as transformers and circuit breakers must withstand. Apparatus insulation as demonstrated by suitable tests must equal or be greater than the basic impulse insulation level and obviously the designer will put in some factor of safety above the required BIL.



Courtesy Westinghouse Electric Corp.

FIG. 8. Auto-valve arrester rated 350 Kv designed for operation on 500 Kv test circuit installed at the Tidd Experimental Area, Ohio Power Company.

The BILs were based upon the levels of protection which lightning arresters of various voltage ratings could meet, under standard test conditions and allowing a margin of safety of the order of 20 per cent. Thus what was tending to become a rather confused situation began to clear, and the past ten years of operation using the BILs have shown the procedure and the tests to be sound, to the end that lightning failures when the arrester protection is provided are very rare indeed.

There has been sufficient confidence developed in the accuracy of the protective levels held by arresters, and in the impulse strength built into power transformers so that for more than ten years the

American Gas & Electric Company has been using so-called grounded neutral arresters rated 109 Kv mounted on 138 Kv transformers built with an insulation level one step below the normal level as shown in Fig. 7. With a grounded neutral system of 138 Kv or more where the system potential is well controlled, good results can be expected, and with good overall economy.

In Fig. 8 is shown a station type lightning arrester having a rating of 350 Kv set up for tests with associated apparatus at the Tidd Plant of the Ohio Power Company.

Successful protection from lightning is not confined to lines and static apparatus, but includes the protection of rotating equipment as motors or generators. This is usually accomplished through the use of capacitors for reducing the turn to turn stress in windings and arresters to limit the potential to ground to a safe value.

Thus as a result of close cooperation between the utilities and the manufacturers, proper instrumentation has been developed, designs of necessary protective equipment made and impulse strength of apparatus determined and coordinated, so that today there is little excuse for interruptions to service or damage to apparatus as the result of lightning.

Today the operation of communications, transportation and the electrical industry depend in large measure upon adaptations of the lightning rod form of protection, developed by Benjamin Franklin.

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EXPERIMENTAL LIGHTNING RESEARCH

BY

HARALD NORINDER[1]

INTRODUCTION

This article deals with experimental research into lightning discharges and effects in their vicinity. The subject matter has therefore been limited by excluding the meteorological aspect of thunderstorms, as well as everything concerned with the origin of the charges in the thunderstorm atmosphere and the conditions under which they occur. Another important branch not touched upon is the long-distance effects of lightning, atmospherics.

Franklin's famous experiments led surprisingly soon to the discovery that lightning is an electric spark, a discovery which is one of the basic facts of lightning research today. From our favored position with regard to technical and physical resources, we cannot but admire Franklin's ability to arrive at conclusions about the nature of lightning which are still up-to-date. It is especially noteworthy that Franklin's observations had an immediate application in the lightning conductor. In writing this article about modern research on lightning, I have found it fitting to devote a good deal of attention to Benjamin Franklin's contributions to lightning research. It is only right to do so now, when it is two hundred years since he made his experiments and drew his conclusions, not least because they have a comparative modernity which may escape the merely superficial glance.

FRANKLIN'S ELECTRICAL EXPERIMENTS IN PHILADELPHIA

Franklin's fascinating progress was largely due to his personal qualities. He showed a rare capacity for observation and a logical ability in drawing conclusions in many fields. It was doubtless also helpful for him that Philadelphia was more or less free from prejudices of tradition. Franklin was therefore able to carry out his experiments and state his conclusions without obstacles set in his way by a lot of preconceived ideas. It was not until he published his results and opinions in Europe that he met with criticism and lack of appreciation.

As the pioneer of an entirely new field of research, regarded, moreover as a self-taught scientist, Franklin experienced a critical climate in Europe colder than that of his home town in America. It is worth noticing what opposition Franklin met with when he tried to convince the learned world that lightning is an electric spark. But the bad start soon gave place to rapid progress.

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[1] Institutet för högspänningsforskning, Uppsala Universitet, Uppsala, Sweden.

Franklin based his contention that lightning is an electric spark primarily on a series of electrical experiments and observations which had been one of his absorbing interests for some years. His correspondence yields us a good deal of information, especially that from the years 1749–1752 with Collinson in London, a Quaker merchant with scientific interests. Experimentation with some glass tubes for electrical experiments that were charged with electricity by rubbing them with silk was the beginning of Franklin's interest in electricity. His experiments enabled him to draw clear conclusions about lightning. In a letter which Franklin wrote to Collinson in May 1750 (and which, according to van Doren (**1**),[2] has eluded Franklin's editors), Franklin writes as follows:

> There is something however in the experiments of points, sending off or drawing on the electric fire, which has not been fully explained and which I intend to supply in my next. For the doctrine of points is very curious and the effects of them truly wonderful; and from what I have observed on experiments I am of opinion that houses, ships and even towers and churches may be effectually secured from the strokes of the lightning by their means.

Franklin made this recommendation about lightning conductors before he was clear about the importance of connecting them with moist places in the soil. It is interesting that he stresses the importance of sharp points in this connection: the corona discharge from points is utilised in modern lightning researches. Hence, when Franklin said in a letter to Collinson "let the experiment be made," he was quite clear about the collector effect of metal points in an electric field. One of Franklin's letters to Collinson, dated 29th July 1750, contains a summary of *Opinions and Conjectures concerning the Properties and Effects of the Electric Matter, Arising from Experiments and Observations made at Philadelphia, 1749.* Concerning the above-mentioned experiment which was to be carried out, Franklin says:

> To determine the question whether the clouds that contain lightning are electrified or not I would propose an experiment to be tried where it may be done conveniently. On top of some high tower or steeple place a kind of sentry box . . . big enough to contain a man and an electric stand (an insulator). From the middle of the stand let an iron rod rise and pass bending out of the door, and the upright twenty or thirty feet, pointed very sharp at the end. If the electric stand be kept clean and dry, a man standing on it when such clouds are passing low might be electrified and afford sparks, the rod drawing the fire to him from a cloud. If any danger to the man should be apprehended (though I think there would be none) let him stand on the floor of his box and now and then bring near to the loop of a wire that has one end fastened to the leads, he holding it by a wax handle; so the sparks, if the rod is electrified, will strike from the rod to the wire and not affect him.

If Franklin had possessed a microammeter to measure the current between the point and the earth, he would have had an apparatus which is still used in lightning research. He would then have found that the discharge current from the point was too weak to discharge the cloud.

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[2] The boldface numbers in parentheses refer to the references appended to this paper.

Franklin certainly did not realise how dangerous his proposed experiment with the sentry-box really was. It was fortunate for both Franklin and the young American Republic which he later served so well, that he never completed the suggested experiment, when we consider the fate of a European investigator who later attempted to carry it out. Franklin thought of erecting his apparatus on a high church tower in Philadelphia, but it was never ready in time.

THE REACTION OF EUROPEAN SAVANTS TO FRANKLIN'S RESULTS—HIS EXPERIMENTS CARRIED OUT SUCCESSFULLY IN FRANCE

Collinson communicated the last-mentioned report from Franklin to the Royal Society, where it was sceptically received and not published. This had the paradoxical effect of making Franklin's researches known to a much wider public: Fothergill, a London physician, urged that Franklin's results should be published, and Collinson gave the article to Cave to be published in his *Gentleman's Magazine*. A separate pamphlet was printed, with the title *Experiments and Observations on Electricity Made at Philadelphia in America* (*1751*) with a preface by Fothergill. It soon became known in France, and Buffon, who recognised the value of Franklin's researches arranged for publication in France. One of his friends, Dalibard, a physicist of good repute, helped with the translation. Together they set about testing Franklin's theories. The Frenchmen were not content with a single apparatus; three were set up at different places in the spring of 1752 by Buffon and the physicists de Lor and Dalibard. The use of three stations simultaneously soon led to results. Such a provision would often have proved useful for modern investigators, who have frequently experienced the disappointment of missing thunderstorms because they have had only one station operating.

Dalibard's apparatus erected on his estate at Marly outside Paris was the first to provide verification of Franklin's expectations. The apparatus used at Marly is shown in Fig. 1. The departures from Franklin's specifications are insignificant. It consisted of an insulated iron pole 40 ft. long and 1 in. thick, with a sharp brass point. Insulation was provided by wine bottles, instead of the resin which Franklin had suggested, and the pole was held upright by silk rope shielded from rain by a metal cover—an experienced physicist's solution of the problem of insulation. The most important difference was that the whole thing stood on the ground, which made it much less dangerous.

A thunderstorm passed over Marly on the 10th May 1752, and successful observations were obtained. Sparks were observed from the insulated pole with a metal arc held by a long insulating handle. Three days later Dalibard delivered a communication to the Académie Royale des Sciences in which he said that he had followed Franklin's instructions and had obtained incontestable proof that Franklin's idea was no longer a conjecture. Some days later both Buffon's and de Lor's apparatuses delivered sparks. The experiments were repeated in many other places in France, and in June of that year le Monnier (2) discovered that there is an electric field in the atmosphere even during fine weather—the normal atmospheric field. The experiments initiated by Franklin thus led to another important discovery.

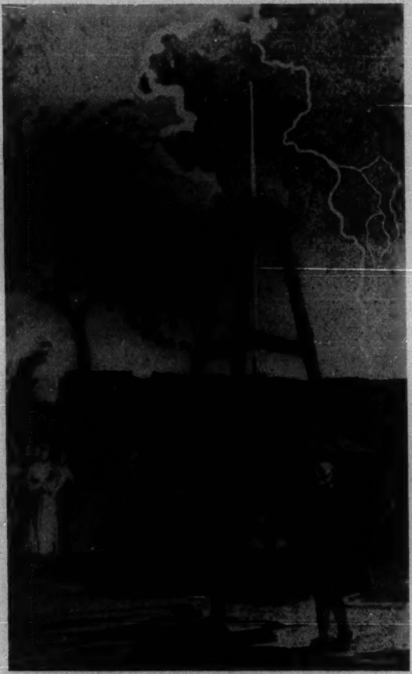

FIG. 1. Experiment of Dalibard at Marly, Versailles 10th May 1752, demonstrating Franklin's idea of lightning's nature.*

De Romas repeated the experiments in July, and varied the conditions. He observed that the length of the sparks depended on the height of the pole—they increased in intensity as the pole increased in height. As a consequence, de Romas (3) conceived the idea of increasing the intensity of the discharge by using a kite, quite independently of Franklin. The first kite experiments were carried out by de Romas in France 1753. Franklin had made incontestable headway in Europe, and his ideas had been confirmed as they deserved to be. His theories were tested at various places in England, France and Belgium during the summer of 1752, but it was not until the 14th September that he heard of the success achieved in Europe. He himself had arrived at the idea of using a kite, and he carried (4) out his famous experiment that summer.

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* For sources of illustrations used in this paper, see p. 504.

The kite experiments carried out by de Romas in France in 1753 are interesting. The kite had an area of 18 square feet, and reached a height of about 180 metres. His experiments were unsuccessful until a thin copper wire was included in the kite cord. Then, on the 7th June 1753, the cord glowed with a corona of 8–10 cm. diameter, despite the fact that it was daylight. Thus, at that early date they knew of the corona around metal wires, which was to prove so important at the present time in the long-distance transmission of electrical energy at high voltages.

De Romas, like the earlier French investigators, was cautious and sensible enough to let the discharge pass to earth through a metal arc held by a long glass insulating handle. This prevented accidents of the kind which happened to Richmann in St. Petersburg. He erected a very well insulated metal pole on the roof of his house, in accordance with Franklin's recommendations, and this led directly to his laboratory. When Richmann during the first test of a thunderstorm came near to the pole, he was killed by a "thunderbolt." It is probable that the pole had been struck directly by lightning. News of this accident soon spread, and was one of the reasons that experiments with lightning stopped almost completely, with one interesting exception. De Romas continued his kite experiments until 1759, and he seems to have entirely mastered the technique. In 1757 he attained spark lengths of 3 metres, and corona discharges of about the same length. So he observed spark lengths which could not be produced in the laboratory until comparatively recently.

Franklin does not appear to have engaged in electrical experiments personally after 1753, but it is certain that he remained interested in this field of research throughout his life. The respect with which he was regarded for his research into lightning resulted in the adoption of his lightning conductors both in America and in Europe. He always retained a personal interest in questions connected with lightning conductors, and his expert advice was often sought.

LIGHTNING RESEARCH DURING THE CENTURY AFTER FRANKLIN'S WORK

Before going on to consider lightning research in the modern sense, we will briefly review the small progress which was made in this field during the century after Franklin's discovery of the nature of lightning. The experimentation which was encouraged by Franklin's initial advance really went as far as it was possible to go with the electrophysical knowledge and equipment which they had at that time. Above all, they lacked measuring instruments.

Another reason which contributed to the lack of progress was undoubtedly that experiments with lightning had proved to be dangerous. It was preferable to follow up le Monnier's discovery, and to study the atmospheric electric field in fine weather. Le Monnier in France and Beccaria in Italy carried out investigations into the normal electric field of the atmosphere at the end of the eighteenth century, making use of the pointed collector which Franklin had so strongly recommended both for his experiments and for lightning conductors.

About 1770, Beccaria (5) constructed an apparatus for recording lightning which was for its time ingenious; he called it the *Ceraunograph.* A small spark gap was arranged between two pointed iron wires. One of the wires was connected to an insulated vertical conductor, and the other was earthed. A strip of thin paper moved between the points, actuated by clockwork. The frequency and size of the holes made in the paper strip by sparks passing between the insulated and earthed wires provided a graphic record of lightning strokes from passing thunderstorms. Apparatuses employing the same principle have been used in modern research as well.

In 1777, Lichtenberg (6) carried out experiments in Germany, in which he used a spark gap between a terminal in contact with an insulating plate and an earthed plate beneath the insulating plate. If a thin powder was sprinkled on the insulating plate, it was found that the powder arranged itself in figures of a peculiar appearance when a discharge passed. The figure for positive charge was different from that produced by a negative. A similar method has been used in modern lightning research, with a photographic plate replacing the powder on the insulating plate. On developing, the photographic plate exhibits figures similar to those observed by Lichtenberg. The modern instruments employing this principle are called Klydonographs.

EARLIER OPTICAL METHODS AND MORE RECENT PHOTOGRAPHIC METHODS IN LIGHTNING RESEARCH

Investigators had already turned their attention to the duration of lightning flashes during the first half of last century. Electrical measuring instruments did not exist, and simple optical methods were tried instead. In 1835 Dove (7) published an account of a device incorporating a rapidly rotating black disc with lighter radial lines. When viewed by the light from a lightning flash, sometimes the radial lines appeared to stay still, and sometimes they appeared to be several times their actual width. The inference made was that the flash consisted of several discharges succeeding one another in the same path. It may be that the method was used somewhat earlier, as Rivière, writing in 1830, says: "It is perhaps necessary to regard a flash of lightning as not just a single electric spark, but as a series of sparks, the first one giving rise to the others." As photography developed, the simple qualitative optical methods were replaced by photographical ones. Because of uncertainties in determining the speed of the moving parts of their apparatus, the earlier workers in the photographic field failed to reach any conclusive result about the total duration of lightning flashes, or about the interval between the subsidiary discharges. Estimations of the duration varied between the instantaneous and times as long as a second. The number of subsidiary discharges was estimated at between 4 and 5, and the interval between them as of the order of up to 1/10 of a second.

The most important photographic research on lightning at the beginning of this century was that of Walter (8), carried out with rotating devices. It was originally certain laboratory experiments with sparks from induction coils that led him to investigate lightning flashes. Walter drew certain conclusions about the way in which a spark develops from photographs of induction-coil sparks. He observed that for both polarities, the spark develops from preliminary discharges which move forward step by step. This was particularly clear for the negative polarity. A photograph of lightning taken by Walter in 1901 is shown in Fig. 2. It comprises 7 separate discharges, with a total discharge period of 0.1 second. They come from a cloud; the one farthest to the left in the figure does not extend to the ground unlike those which succeed it. Walter's photographic methods were

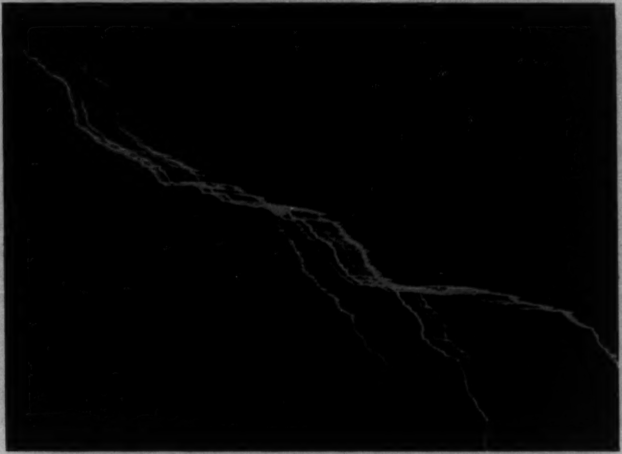


FIG. 2. Photograph taken 1901 by Walter's rotating camera of seven discharges in the same path.

interesting and capable of development, but almost 30 years passed before similar methods were resumed.

INSIGNIFICANT PROGRESS OF LIGHTNING RESEARCH DURING THE FIRST TWO DECADES OF THIS CENTURY

At the end of last century, lightning conductors began to be standardized technically. This brought to the fore the question of the currents involved in lightning discharges. Several well known physicists were consulted, and the melting effect of lightning was used for measurements. Kohlrausch (9) calculated the melting current to be 52.000 amperes for a duration of 0.001 second, 9200 amperes for 0.03 second, for a copper wire 5 mm. in diameter. Humphreys (10) calculated that the current which crushed a copper tube was 90.000 amperes. These values agree with later results.

Pockels (11) worked out an important method for measuring the current involved; this made use of the remanent magnetism in basalt rods placed near the conductor through which the discharge had passed. Three such basalt rods gave values of 10.800, 6.600 and 6.450 amperes, and in one case 11.000 amperes. The method is still used in the so-called magnetic links, although basalt has given place to thin wires or strips of hard steel.

There was hardly any advance in lightning research during the first two decades of this century, except for some photographic results, in contrast to the headway made in allied fields of scientific activity. At that time some people even supposed that lightning was an oscillatory discharge, with a frequency in the neighbourhood of half a million cycles per second. A critical voice was raised against this conception of lightning, in an article in this JOURNAL (12), in which it was demonstrated theoretically that, with feasible values of self-induction and capacity in the discharge circuit of a vertical flash, a resistance of the order of 200 ohm/km. was all that was needed to render a discharge aperiodic. Later on, investigations (13) in Uppsala of the resistance in long artificial sparks carrying heavy currents up to 100 kiloamperes resulted in internal resistances of the sparks of the same order of magnitude or 200 ohm/km.

ELECTRIC POWER DISTRIBUTION STIMULATED LIGHTNING RESEARCH

A change of attitude with regard to lightning research occurred later in this century. The extremely rapid development of grid systems for the transmission of electric power brought with it the need for systematic research into the ways of lightning. Lightning caused in transmission lines disturbances which were troublesome for the transmission system and for electrical installations. A knowledge of the variation properties of lightning was required for the design of protective measures. With such knowledge it would become possible to reproduce the form of the discharges under controllable conditions in the laboratory—a necessary condition for the construction and testing of suitable protecting devices.

The fact that such research was commenced in Sweden, despite the low frequency of thunder-storms there compared with Central Europe and the United States, depended on two circumstances. The author had been working with problems of atmospheric electricity for some ten years, and had been struck by the strength of the disturbances in the electric field which were caused by thunder-storms. A direct application was made to the Swedish Royal Board of Waterfalls, the organization responsible for the important high tension lines of Sweden. It was proposed that there should be systematic research into lightning, in view of the trouble it caused in transmission lines. The proposal was accepted, and the investigations began in 1919. Quite independently, B. John F. Andersson and his wife gave a donation to Uppsala University at about the same time for a professorship in electrophysics, and for an institute for lightning research. The donation was devoted to the Institute for High Tension Research at Uppsala University, when this was subsequently established.

SWEDISH RESEARCHES INTO THE ELECTRIC FIELD VARIATIONS DUE TO LIGHTNING

The first task of investigation in Uppsala was the intensities of electric fields met with in thunder-storms. These proved to be considerably higher (**14**) than had previously been supposed. Field intensities of up to 100 Kv/m. were observed during violent thunder-storms. Later measurements, by Gunn (**15**) carried out in thunder-clouds from aeroplanes equipped with rotating voltmeters, gave average values of 130 Kv/m., collected from nine different storms. According to Robertson, Lewis and Foust, investigations (**16**) have been carried out with three ground stations at different places in America. Measurements were made with a microammeter in conjunction with a rod collector, and values of as much as 300 Kv/m. were obtained, and 69 separate field records provide a mean value of about 100 Kv/m. It follows from these values that only a limited part of a thunder-cloud can be discharged by a flash of lightning.

The main problems investigated in Sweden became quite soon the discharge properties of lightning and their dependent effects, the lightning surges on transmission lines. It was found that the only suitable instrument for this investigation was the cathode-ray oscillograph, and a research laboratory was set up in 1922 just outside of Uppsala.

One of the first questions to be determined was whether lightning was oscillatory or not. Experiments were begun in 1921, with an apparatus including an open aerial connected to earth through a resistance which damped out any self-oscillations of the aerial. The aerial picked up field variations radiated by nearby lightning discharges. The voltage variations over a certain fraction of the aerial resistance were measured with a Braun-type oscillograph. It needed no more than direct ocular observation to show that the discharges were neither of high-frequency nor even oscillatory. In 1922 an optical recording device was introduced and the results were published in Sweden (17) and somewhat earlier in the U.S.A. (14). The results were *a priori* important for the problem of lightning surges on transmission lines, as it was possible to conclude that the surges must also be aperiodic.

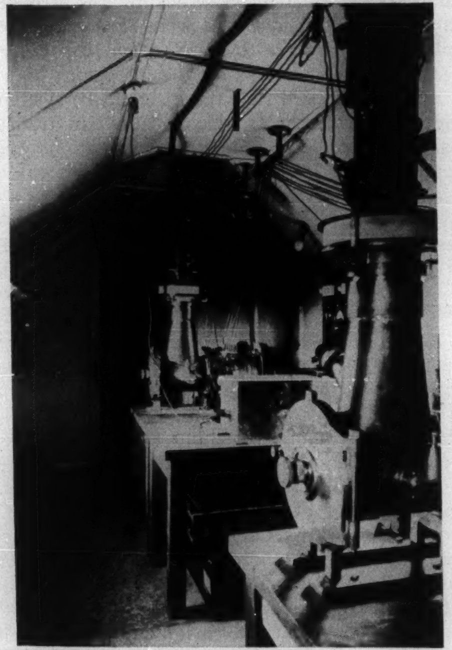


FIG. 3. View of two cathode-ray oscillographs with special electron beam relay installed in movable laboratory for lightning researches.

A HIGH-SPEED RECORDING CATHODE-RAY OSCILLOGRAPH OF SPECIAL DESIGN REVEALS THE SECRETS OF LIGHTNING

A special cathode-ray oscillograph capable of high-speed recording was found to be necessary for the investigations. During the first World War Dufour (18) constructed such a cathode-ray oscillograph in which the electron beam impinged directly on a film in the vacuum. It was possible to record variations of voltage down to fractions of a microsecond. I visited Dufour's laboratory in Paris in 1922 to try to interest him for an application, and I suggested that the oscillograph opened up a wide range of possibilities both for natural flashes and for artificial lightning, indispensable to the production of devices for protection against lightning surges. The oscillograph was very convenient in application, but I found when it came to recording variations from a lightning discharge the oscillograph was not at all suitable. Hence, it became necessary to construct an instrument provided with a relay which would set the recording device in action without delay for registration of the very rapid lightning variations. The electronic valves had not then been developed to the stage where it was possible to use them to construct an electronic relay. I therefore made the electron beam itself in the oscillograph function as a relay so that the voltage variation of the lightning or of the surge itself brought the electron beam into action to record (**19**) the course of the variation. The oscillograph which was built is illustrated in Fig. 3 where two of them constructed for the lightning investigations are shown in one of the laboratory's field wagons.

THE FIRST RECORDINGS OF LIGHTNING SURGES

The relay allowed the author to take the first recordings (**20**, **21**) of surges caused by lightning in transmission lines in 1925. The line was operated at 20·Kv, and was coupled to the oscillograph through a capacitance potentiometer. The first oscillograms are shown in Fig. 4.

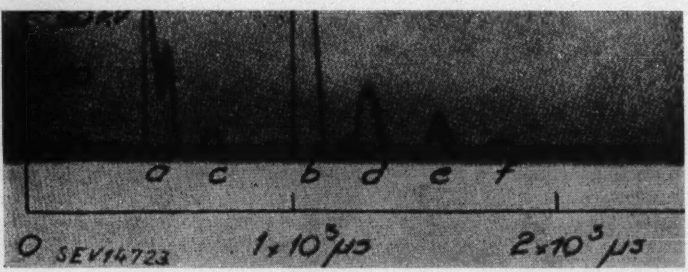


FIG. 4. Records of lightning surges on transmission line obtained at Uppsala 1925 by cathode-ray oscillograph with special electron beam relay.

The lightning flash which caused the surge occurred at a distance of about 5 km. from the observation station, which explains the straight fronts. Two primary lightning surges, *a* and *b*, can be seen in Fig. 4, as well as reflections *c*, *d*, *e* and *f*. The total duration of the surge was a little more than 100 microseconds (μsec). Quite a large number of lightning surges were recorded between 1925 and 1927.

The oscillograph also proved to be suitable for the investigation of lightning discharges. The aerial circuit was used to record the variations of the pre-discharge, of the main discharge, and of the multiple discharges. So lightning discharges were investigated directly during the same period when the first lightning surges on transmission lines were being recorded in Sweden. Oscillograms for lightning flashes are reproduced in Fig. 5, where it will be seen how complicated lightning discharges can be and that lightning often exhibits a succession of discharges with rapid superimposed field variations. These provoke the unavoidable disturbances in radio receivers in thunder-storm regions.

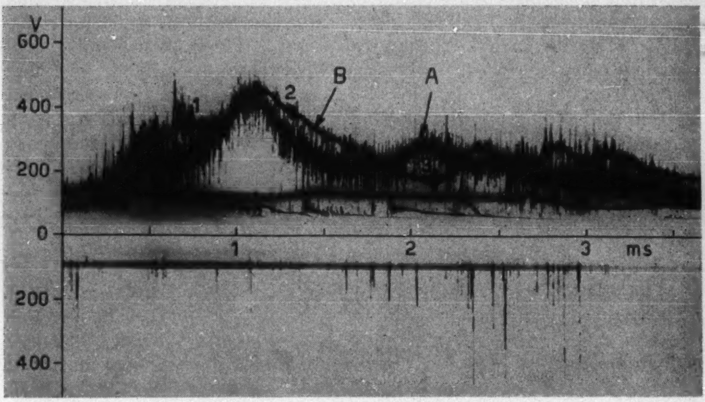


FIG. 5. Cathode-ray oscillograms of lightning discharges taken at Uppsala with open antenna circuit. On curve A superimposed rapid field variations all over, on curve B most at beginning 1 and later on at 2, 3.

MODERN LIGHTNING RESEARCH IN THE UNITED STATES OF AMERICA

Obviously lightning research in the U.S.A. would assume different proportions, compared with a country like Sweden. The frequency of thunder-storms is considerably greater, and the distances had given rise to long electric transmission lines. Therefore, damage and disturbances due to lightning were on a much larger scale in the United States than in Sweden, or other European countries.

Lightning research really got under way in the United States about a quarter of a century ago, sponsored by the large electrical concerns, the General Electric Company and the Westinghouse Company, and by firms supplying electric power. Intimate cooperation between them was established. It was in the main young engineers who were entrusted with the research, which necessitated the solution of many intricate problems. To begin with this work was confined to the surges on high-tension lines, caused by lightning discharges, a limitation made for technical reasons. The variation in lightning surges was studied, both the time in microseconds taken for the voltage to reach its crest value, and the total duration and polarity. The values involved were necessary for the construction of lightning arresters.

The development in this field may be seen in the Lightning Reference Book (22) published by the American Institute of Electrical Engineers with reprints of articles published between 1918 and 1935.

There is a decisive increase in the work after 1928, since the use of the cathode-ray oscillograph opened up a host of new possibilities in research. It would have been a good thing to have investigated the lightning discharges themselves at the same time as the large-scale investigations into the surge voltages in high-tension lines. In this way, some more insight into the nature of lightning and its connection with the surges produced would have been obtained. There was only a limited number of cathode-ray oscillographs available, and it is probable that there was thought to be insufficient time for such comprehensive research: it was necessary to obtain practical results as quickly as possible for the construction of lightning surge-arresters and for other protective measures in electrical installations.

RESULTS OF LIGHTNING SURGES FROM FIELD STATIONS CONNECTED TO HIGH TENSION LINES

The General Electric Company and the Westinghouse Company set up several field stations during 1928 and 1929 for the study of lightning surges. The first lightning research station of the General Electric Company was installed in 1928 on the Wallenpaupack-Sigfried 220 Kv line of the Pennsylvania Power and Light Company. A special method (**23**, **24**) of conveying the surge to the cathode-ray oscillograph was used at this station. This method has frequently been utilised since then for recording artificial lightning surges. The first lightning surge recorded in this way in 1928 at the Wallenpaupeck station is shown (**24**) in Fig. 6. The crest voltage of the surge was approximately 600 Kv.

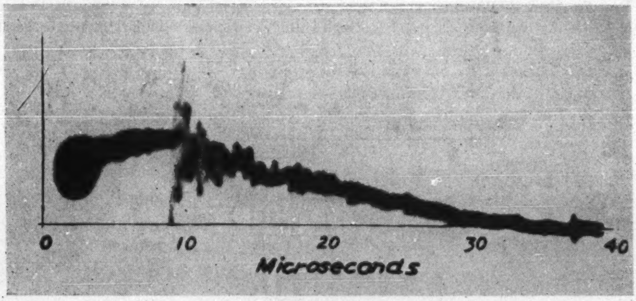


FIG. 6. Cathode-ray oscillogram of lightning surge on 220 Kv line taken 1928 at General Electric Company's Wallenpaupack laboratory for lightning research.

The Westinghouse Company installed their first station in 1928 in Tennessee, on the 154 Kv Cheoah-Alcoa line of the Aluminum Company of America. A view of the external arrangements of such a station is reproduced in Fig. 7. The author's relay (**19**) was used with the cathode-ray oscillographs at this and all other stations of the Westinghouse

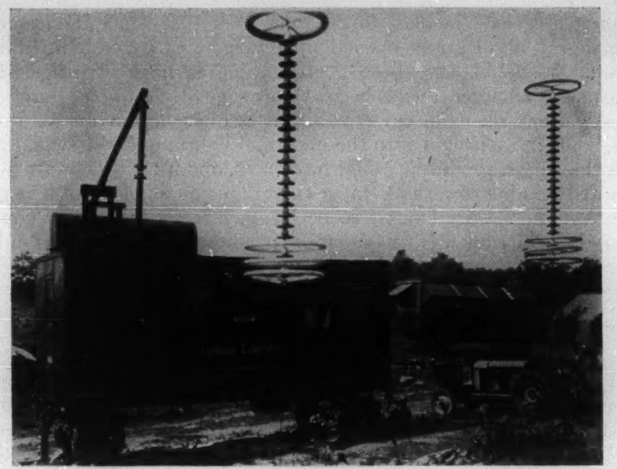


FIG. 7. View of Westinghouse Company's portable laboratory for lightning researches with cathode-ray oscillographs. In front high voltage capacitance potentiometers on insulator strings.

V.
19

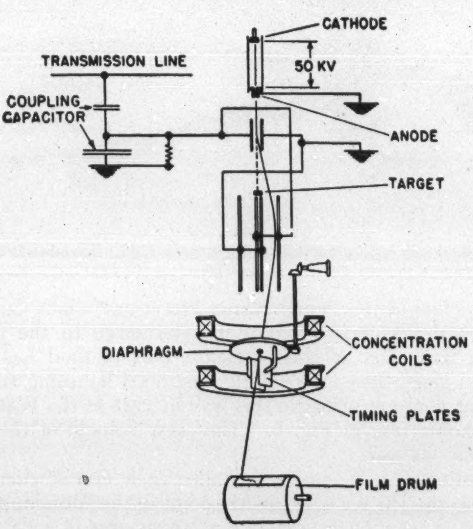

CATHODE
TRANSMISSION LINE
50 KV
COUPLING CAPACITOR
ANODE
TARGET
DIAPHRAGM
CONCENTRATION COILS
TIMING PLATES
FILM DRUM

FIG. 8. Electron beam relay of cathode-ray oscillograph connected for recording lightning surges to capacitance potentiometer of transmission line.

Company. The diagram of Fig. 8 shows that the relay prevented the electron beam from impinging on the film normally. When a surge arrives, a voltage is applied to the deflector-plates via a potential divider. The field between the counter-coupled system of plates forces the beam to bend round the blocking target to reach the film. The advantage of this relay is that it does not give rise to any time lag in recording the surge.

A typical group of seven surge oscillograms obtained at the Westinghouse studies (25) and taken in 1929 with oscillographs provided with this relay is reproduced in Fig. 9. They were taken at various stations; one on the 220 Kv Bushkill-Roseland line of the Public Service Company of New Jersey, one on the 154 Kv Cheoah-Alcoa line, and another on the 132 Kv Turner-Logan line of the Appalachian Electric Power Company in West Virginia. It follows from the curves that the front value may be between 2.5 and 6 μsec, and similar values have been obtained in other investigations. The short duration indicated by the times to half-peak values of the tail of the surge are noteworthy.

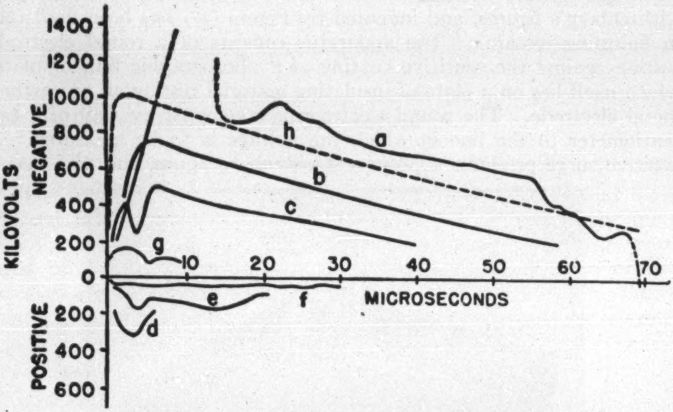


FIG. 9. Lightning surges recorded with the electron beam relay in 1929 in New Jersey, Tennessee and West Virginia.

A particularly interesting result is that obtained in 1930 by one of the Westinghouse Company's field stations (26) on the 110 Kv line of the Arkansas Power and Light Company. This line was a very well insulated wooden-pole line without a protecting ground wire. An oscillograph of the relay type was connected to the line through a highly insulated capacitance potentiometer. The oscillogram showed that a surge of negative polarity with a crest value of 5 million volts (5000 Kv) was registered. This crest value was reached in less than 2 μsec. The maximum rate of the rise was of the order of 4000 Kv per μsec. Another negative surge of 4500 Kv, where the crest was reached in about 1 μsec. was also recorded during the same thunder-storm. In these cases surges were obtained when lightning struck the line directly. The distance between the place where the lightning struck and the oscillograph station was 4 miles, that is, 6.4 km. So the crest values occurring when a line is struck directly are dependent on the degree of insulation in the two cases mentioned very high, because the line was supported on wooden poles.

KLYDONOGRAPHS VALUABLE INSTRUMENTS IN LIGHTNING RESEARCH

It has already been mentioned that the klydonograph, based on Lichtenberg's figures, and invented by Peters (27) has been used (28) in lightning research. The apparatus consists of a round electrode resting against the sensitive coating of a photographic film or plate, which itself lies on a plate of insulating material resting on an earthed metal electrode. The round electrode is connected by way of a potentiometer to the line in which the voltage is to be measured. A positive surge produces a positive Lichtenberg figure, and vice versa.

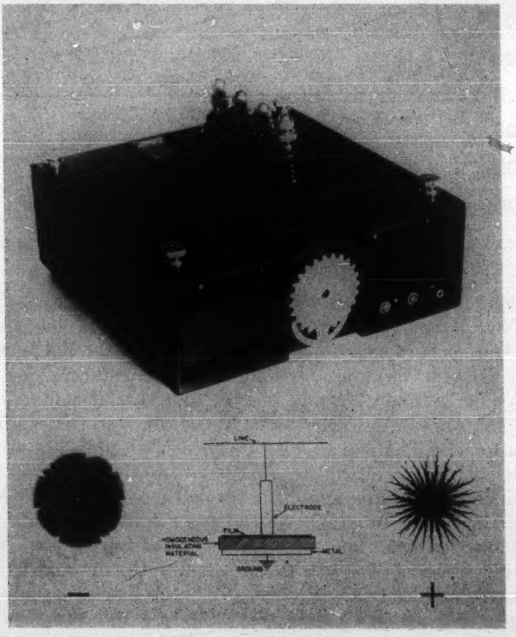


FIG. 10. Klydonograph constructed at Westinghouse Company. To left negative and to right positive Lichtenberg figures; between, recording principle of klydonograph.

It was found that the figures were produced even if the surge voltage lasted only for a fraction of a microsecond. The radius of the figure provided a measure of the voltage to an accuracy of within 25 per cent. The accuracy was greater for positive figures, and Foust (29) introduced a device into the circuit which produced a positive figure whatever the direction of the flash. This type of klydonograph was called a surge-voltage recorder, and was inexpensive. A large number of them could therefore be connected to power lines. Many measurements with klydonographs, see Fig. 10, have been carried out on surges in high-tension lines. On normally insulated lines, voltages as high as 15 times the normal line-to-neutral peak voltages have been recorded, and on over-insulated lines up to 21 times the normal peak voltage. It has also been possible to measure the attenuation with distance from the origin of the surge. Measurements of the voltage between the top of a tower and the ground gave a maximum of about 100 Kv, which indicates that the tower current has a slow rate of rise.

INDUCED LIGHTNING SURGES ARE OF IMPORTANCE FOR LOW-TENSION DISTRIBUTION LINES

The surges caused by direct strokes are relatively rare, and those induced in transmission lines by flashes which do not strike them directly are more common. Bewley (30) has given a theoretical treatment of them. The extensive subsidiary lines at medium or low voltages are very much affected by these induced surges. In view of their extent and importance, I thought it desirable to carry out a syste-

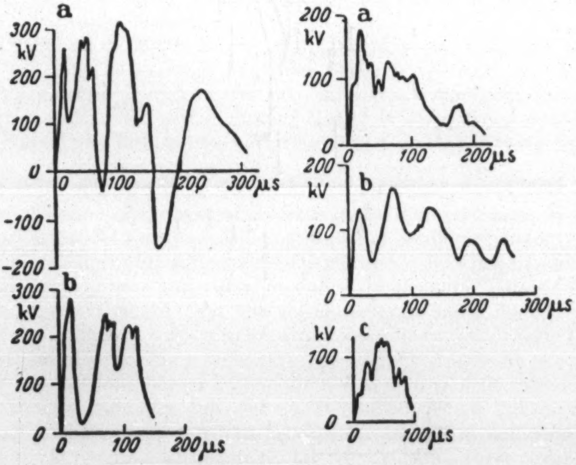


FIG. 11. Records of induced lightning surges from test line at High Tension Research Institute, Uppsala University.

matic investigation of the disturbances (31) affecting them. This was one of the first tasks in field of lightning surges undertaken by the Institute of High Tension Research of Uppsala University after its inauguration in 1932.

A special test line 13.5 km. long was constructed, with a surge insulation level of 1150 Kv. The oscillograms were taken at one end of the insulated line, and the other was connected to earth. So the double voltage was recorded at the measuring end. Records, exemplified by Fig. 11, were made during two thunderstorm seasons and Fig. 12 gives the amplitudes in relation to the distance for flashes whose position was observed.

RESEARCH INTO LIGHTNING SURGES CREATED A NEW TEST METHOD FOR ARTIFICIAL LIGHTNING

The purpose of these comprehensive investigations into the lightning surges on transmission lines was, as mentioned, to obtain data for the

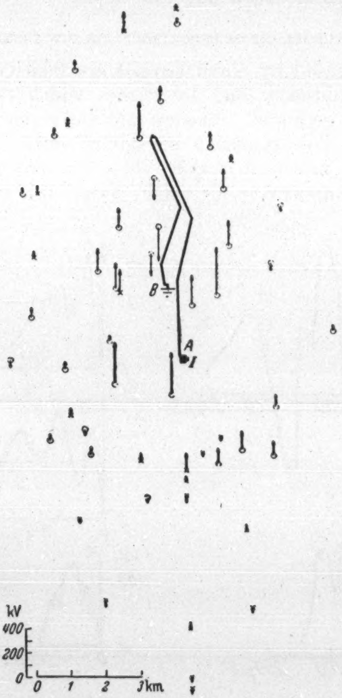


FIG. 12. Induced lightning surge voltage amplitudes in relation to distances between test line and observed lightning paths.

construction of protective devices, particularly lightning surge-arresters. The results also provided useful information for the production of artificial lightning discharges in the laboratory. Impulse generators for both voltage and current surges were used for these discharges, and, by a combination of the two, Bellaschi (32) was able to make artificial lightning with a surprising resemblance to the natural lightning in many respects.

These generators have made it possible to develop an entirely new testing technique for insulators and other electric equipment during recent years. These tests render the older methods, which employed alternating voltages, obsolete in many respects. The cathode-ray oscillograph occupies a key position in this impulse testing technique and one may say that the measurements would not be possible if it were not for this technique. The primary use of the cathode-ray oscillograph is for determining the wave-shape of the voltage and current impulses. It was not long before a standard impulse test wave was introduced. In the United States it is given as 1.5 × 40 μsec, where the first number signifies the time to the crest and the second the time to the half-crest value of the tail. The International Electrotechnical Commission have accepted two types of test wave, 1 × 5 and 1 × 50 μsec.

Laboratory technique for impulse tests is also very important for lightning research in its proper sense. As was found later on, the study of artificial long electric sparks enables us to observe certain phenomena analogous to those associated with the development of natural lightning flashes.

Investigation of the surges on high-tension transmission lines has thus not only stimulated lightning research indirectly. There is a direct connection between the two, in that the aperiodic form of the variations observed with lightning surges is very strong confirmation of the aperiodic form of the variation of the actual lightning discharge.

A NEW TREND APPEARED WITH INVESTIGATION OF VARIATIONS IN LIGHTNING CURRENTS

At the time of the economic crisis in the United States in 1930–31 several of the field stations using cathode-ray oscillographs for the measurements of lightning surges were dismantled. It is not possible for an outsider to say how much this depended on economic factors, and how much it was thought that the measurements had achieved all that could be achieved. A contributory reason may have been that the experimental experience seemed to be bought dearly in one respect, for it was not long before it was discovered that violent thunderstorms near to a transmission line did not necessarily cause lightning surges in it. It therefore proved to be difficult to obtain sufficiently comprehensible results with regard to the variations of these surges within a fairly short period of observation.

Whatever the facts of the matter, a new tendency appeared in lightning research during the 1930's, when a direct study of the mechanism of discharge began. This gained in interest from the fact that it had been observed, both in the U. S. and in Europe, that the dangerous surges for lines operating at high voltages, that is, over 60 to 70 Kv, were caused by lightning (33) striking them directly. Considerable attention was therefore paid to determination of the current characteristics of lightning. The problem also had a certain pure scientific interest.

The investigation of the currents was facilitated by the introduction of the magnetic link method (34), a modern application of Pockels' method using basalt rods. The magnetic link consists of a small bundle of cobalt-steel laminations or wires inserted in a cylindrical moulded plastic container or a small airtight glass tube, see Fig. 13.

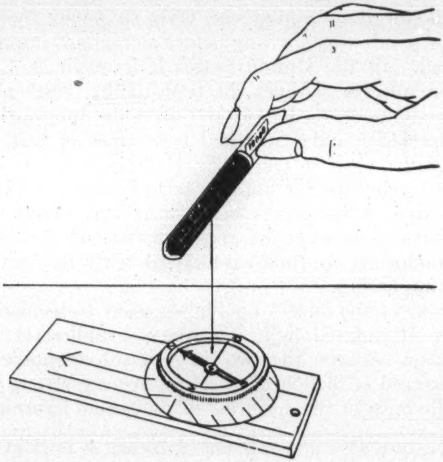


FIG. 13. Magnetic link—a small bundle of cobalt-steel wires in air tight glass tube with compass for indication of magnetization by lightning current.

The former type has been used in the U. S. A., and the latter in Germany and Sweden. Usually, two of these links are mounted at different distances from a conductor, on a wooden bracket fastened to the conductor. The principle of the measurement is that the current flowing in the conductor sets up a magnetic field proportional to the current. This field magnetizes the link mounted in the direction of the field at a certain distance from the conductor. The link retains a certain residual magnetization, which can be measured with a suitable instrument. The current that produced the residual magnetization may be obtained by an experimental calibration. The method assumes that the current is unidirectional. It has been shown that surge currents, of however short duration, leave the same residual magnetization as a direct current of the same magnitude.

After a thunder-storm, the link is removed from the bracket, and tested with a compass; see Fig. 13, if magnetized, the link is placed in a protective shield of soft steel, and taken to the laboratory for measurement of the peak current values. These links have been placed on the legs of transmission towers, on down leading conductors of ground wires, on lightning conductors, and in the earth connections of lightning surge-arresters. One advantage of the magnetic link method is its cheapness and ease of operation. There have been various modifications of the link method. The fulchronograph (**35**) (Fig. 14) is one of these: it is a device which may be used in place of an oscillograph, as it allows the variation of the current with time to be measured.

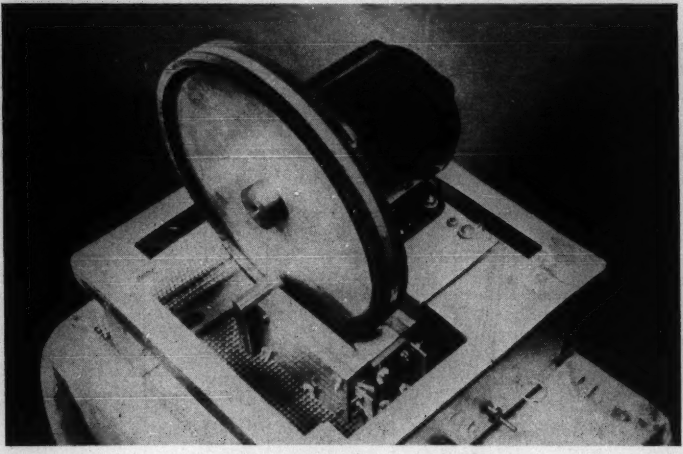


FIG. 14. Fulchronograph, a device capable of measuring wave shape and duration of tail of lightning current surges.

DIFFERENT METHODS OF MEASURING LIGHTNING CURRENTS

The variation of lightning currents has been measured for various types of object:

A. Low Objects

(1) lightning conductors on low chimneys and buildings have been used;
(2) towers and ground wires of transmission lines; or
(3) lightning arresters.

B. Tall Objects

(1) Stekolnikov and Valeev (**36**) in Russia measured lightning currents to captive balloons at altitudes between 500 and 800 m., using the cathode-ray oscillograph or high-speed rotating klydonograph;

(2) McEachron (**37**) measured the current in lightning which struck the Empire State Building in New York using cathode-ray or crater-lamp oscillographs and magnetic links; and

(3) Wagner, McCann and Beck (**38**) measured the currents in tall objects of different heights with the fulchronograph and other devices based on the magnetic link.

C. Frame Aerial Method

Magnetic field variations due to vertical lightning strokes were measured by Norinder (**39**), Norinder and Dahle (**40**) in Sweden, and corresponding lightning currents calculated from them.

Measurements in category *A* are very numerous, especially for 1 and 2. A full list of references is given in a comprehensive article by Wagner and McCann (**41**) in the Electrical Transmission and Reference Book issued by the Westinghouse Company.

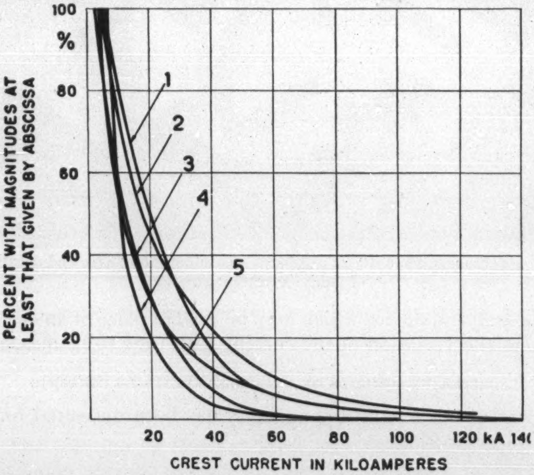


FIG. 15. Crest current in kiloamperes. Percentage distribution curves of tower currents (1, 3, 4, 5) for strokes to transmission lines and (2) calculations from magnetic field measurements.

1. Lewis and Foust	(42)	734 records
2. Norinder and Dahle	(40)	104 records
3. Waldorf	(43)	1201 records
4. Grünewald	(44)	1689 records
5. Bell	(45)	370 records

The peak values of lightning currents in earthed objects are important in recent research. There are sufficient observations available now, especially with regard to towers to take them as representative for lower objects. The curves in Fig. 15 give percentage distribution of lightning currents in transmission-line towers, with a lower limit of 2400 amperes for 3 and an upper of 5000 amperes for 1, 4, 5. The latest published values (40) obtained in Sweden with the improved frame aerial method are given for comparison. These values and values of 4, recorded in Europe, agree well with the results 1, 3, 5 obtained in the U. S. A.

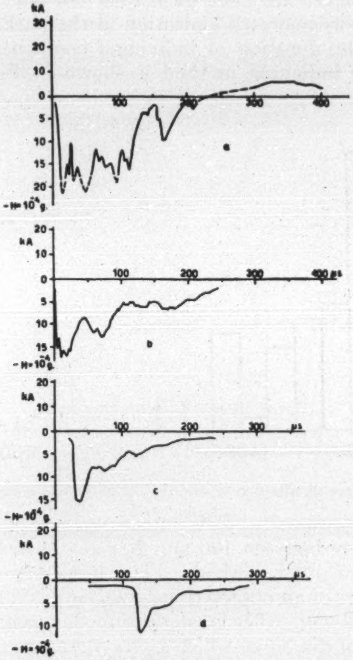


FIG. 16. Consecutive current components in a vertical lightning flash.

Individual values in excess of 200,000 amperes have been measured in the U. S. The mean of peak current values from about 2700 individual observations is about 10,000 amperes. Negative flashes, that is, flashes from a negative cloud charge, predominate, varying from 67 to 97 per cent of the observations, with an average of 82 per cent.

Various methods have been employed for the investigation of the number of component discharges in the complete discharge, the time interval between them, their duration, and the total discharge time. But the results obtained do not agree particularly well which suggests that further work is desirable.

The variation forms of the succeeding components of a flash usually resemble one another. This is to be expected, since the charge in the cloud and the field associated with it do not have time to change during the brief time the discharge lasts. A typical example of the consecutive components from a vertical lightning flash is given in Fig. 16, a record by the magnetic induction method (**40**). The two lower discharges in that figure are more even than the ones above; this is explained by the persistence of ionization in the path. The percentage distribution of the duration of individual components oscillographed by the magnetic induction method is shown in Fig. 17. The most common values are between 100 and 200 μsec, which is in full accord with the results of other methods. The 1000 μsec component shown in Fig. 17 was part of an observed flash which killed a man and set fire to a wagon-load of hay. The crest value of this component was 20,000 amperes, a type of discharge which is very dangerous for transmission lines.

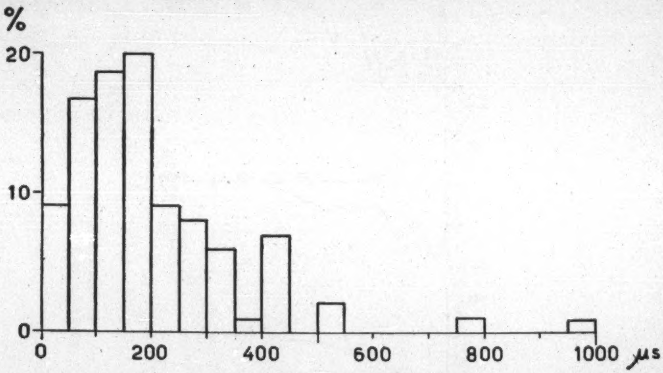


FIG. 17. Percentage distribution of duration of individual components in multiple lightning strokes.

The charge transported in lightning striking tall objects seems to be greater than for lightning striking lower objects or open ground. The distribution of values obtained for individual components in vertical flashes to the ground with the magnetic induction method showed that the majority of values are less than 5 coulombs. If the total discharge of a lightning flash is calculated on a basis of the usual number of components, the most usual values for this total must be from 10 to 15 coulombs. McEachron (46) has reported total values in excess of 160 coulombs for lightning striking the Empire State Building, and Wagner, McCann and Beck (38) obtained total values of 60 coulombs for the Cathedral of Learning at the University of Pittsburgh. These high values of the transported charge must to a certain extent be due to the intense local field around tall objects.

INVESTIGATIONS OF LIGHTNING DISCHARGE MECHANISM BY PHOTOGRAPHIC METHODS

It was not until the 1930's that photographic methods were again taken up, after Walter's experiments at the beginning of the century. A special camera was used, which had been developed by Boys (47) in 1902. It consisted essentially of a rotating plate carrying two lenses

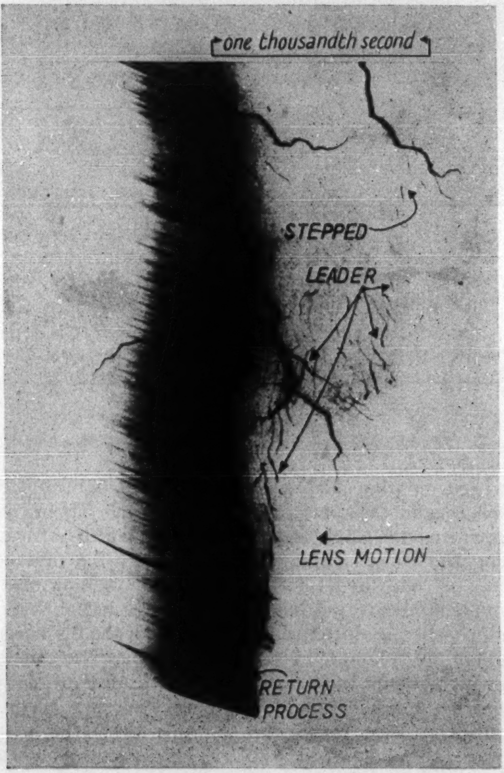


FIG. 18. Boys-camera photograph by Schonland showing stepped leader.

which moved in opposite directions at any instant. In photographing a lightning discharge, the two images were displaced and the velocities of the components of the flash were determined by a comparison of the two pictures, the focal lengths of the lenses, their velocities, and the distance of the lightning being known.

Boys did not secure a satisfactory picture of lightning himself. The first successful pictures were obtained by Schonland (**48**) and his associates, when they took up the work in 1933 in South Africa, using Boys cameras. McEachron and co-workers (**49**) used the Boys camera from 1935 to 1941 to photograph lightning discharges at the top of the Empire State Building.

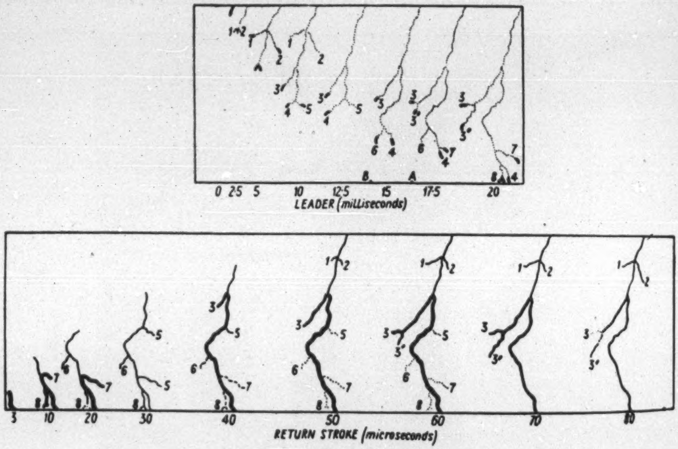


FIG. 19. Mechanism of discharge according to Schonland.

As has been mentioned elsewhere, a flash of lightning consists of several discharges in the same path, and the Boys camera was a convenient apparatus for analysing them. The South African investigators, using the Boys camera, discovered that the first component discharge was preceded by a pilot streamer into virgin air at a low state of ionization, and of too low a luminosity to be recorded by the camera. Its existence was deduced from the mechanism of the discharge. These pilot streamers are followed by points of luminescence that travel in steps, and which are therefore called stepped leaders; a photograph of one of them from a publication of Schonland's is reproduced in Fig. 18. When the leader strikes the ground, a return discharge is propagated upward towards the cloud, see Fig. 19. This discharge follows the same path as the downward leader. The subsequent discharges are pre-

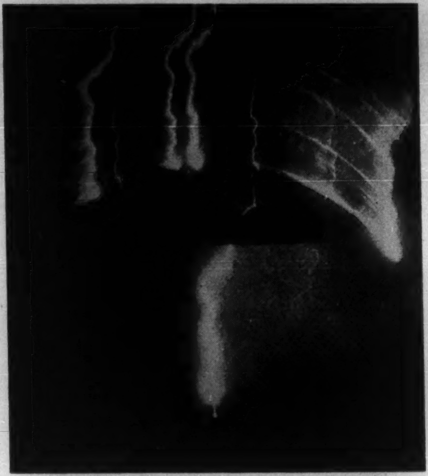
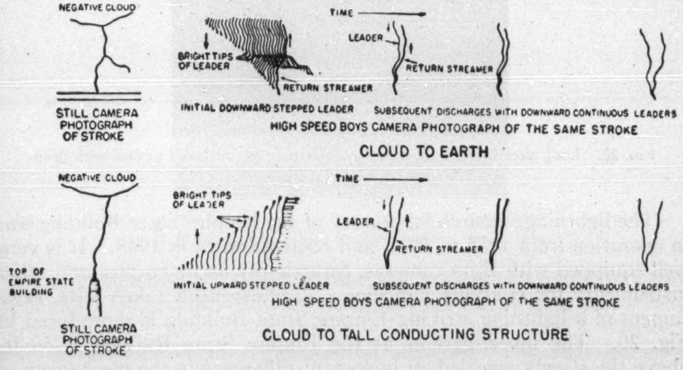


FIG. 20. Boys-camera photograph of stroke to Empire State Building consisting of an initial long-continuing discharge followed by six subsequent discharges.

ceded by a dart or continuous leader that travels in the ionized channel of the first return stroke.

The South African research shows that the stepped leaders proceed from cloud to earth with a velocity varying from 10 to 2000 cm./μsec. The pause between the steps varied from about 30 to 90 μsec, and the length of each step varied from 10 to 200 m. The subsequent strokes



NEGATIVE CLOUD
STILL CAMERA PHOTOGRAPH OF STROKE
TIME
BRIGHT TIPS OF LEADER
RETURN STREAMER
LEADER
RETURN STREAMER
INITIAL DOWNWARD STEPPED LEADER
SUBSEQUENT DISCHARGES WITH DOWNWARD CONTINUOUS LEADERS
HIGH SPEED BOYS CAMERA PHOTOGRAPH OF THE SAME STROKE
CLOUD TO EARTH
NEGATIVE CLOUD
TOP OF EMPIRE STATE BUILDING
STILL CAMERA PHOTOGRAPH OF STROKE
TIME
BRIGHT TIPS OF LEADER
LEADER
RETURN STREAMER
INITIAL UPWARD STEPPED LEADER
SUBSEQUENT DISCHARGES WITH DOWNWARD CONTINUOUS LEADERS
HIGH SPEED BOYS CAMERA PHOTOGRAPH OF THE SAME STROKE
CLOUD TO TALL CONDUCTING STRUCTURE

FIG. 21. Diagram evidencing discharges from negative cloud to flat terrain and discharges from negative cloud to tall structures such as Empire State Building.

have a continuous or dart leader proceeding from the cloud with a velocity ranging from 100 to 2600 cm./μsec. Both stepped and continuous leaders which reach the ground are followed by main or partial return streamers proceeding from the ground to the cloud. Their velocities range from 2000 to 14000 cm./μsec, 1/15 to 1/2 the speed of light.

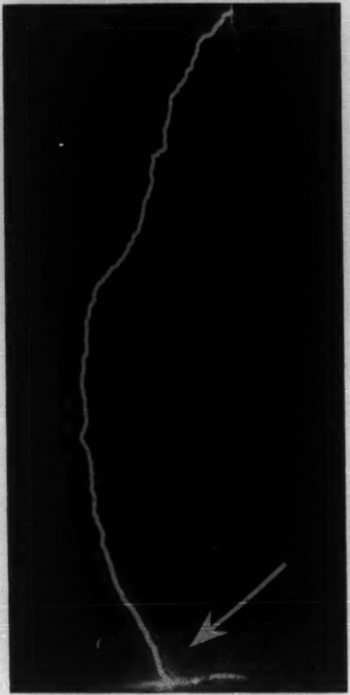


FIG. 22. Long electric spark from positive electrode against sand surface with dead-running leader, see arrow.

The lightning research laboratory of the Empire State Building was in operation from 1935 to 1941, and resumed work in 1948. It is very well equipped with Boys cameras, cathode-ray oscillographs, and other instruments for studying lightning. A photograph taken with Boys camera of a lightning striking Empire State Building is reproduced in Fig. 20. The investigations at the Empire State Building 1250 ft. above the streets revealed an important difference in the mechanism of the discharge as compared with the South African results. The initial stepped leaders were in the opposite direction: they went from the top of the building to the cloud. They were not followed by return streamers. This difference is illustrated in Fig. 21. The continuous leaders of subsequent discharges proceeded downward from cloud to earth, and all the return discharges were upward from earth to cloud. In other respects, however, these investigations confirmed the general conclusions drawn from the South African investigations. For further information, the reader is referred to a comprehensive article by McEachron (**49**) in this JOURNAL.

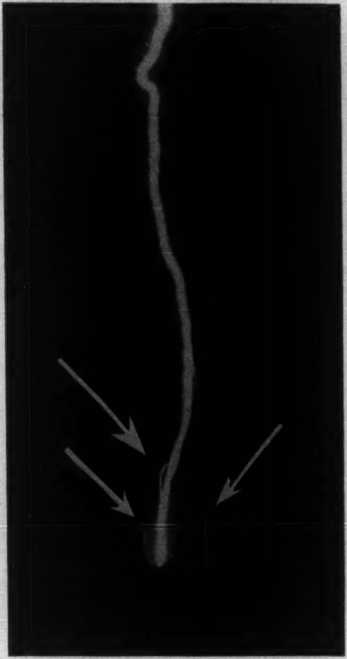


FIG. 23. Natural lightning striking sand surface of beach in New Jersey. Camera 30 m. from flash, showing dead-running leaders, see arrows.

The explanation of the fact that the leaders propagate upwards from the Empire State Building is that the building acts like a long needle above a lower level surface. It therefore causes considerable disturbance of the equipotential surfaces. The field intensity developed at the top of the tower attains such a high level that discharges develop from the top and propagate upwards.

There appears to be no physical reason why upward leaders should not develop upwards from the more or less flat surface of the ground, to meet leaders moving downwards. Model tests carried out at Uppsala (50) with long sparks against a flat surface of dry sand have shown that such leaders do develop, for both positive and negative sparks: see the arrows of Fig. 22. It is interesting to compare this picture of an artificial discharge with the photograph of natural lightning striking a sand surface at a beach in New Jersey. In this case the camera happened to be placed at a distance of 30 m. from the flash. Two dead-running leaders, see the arrows in Fig. 23, are visible, the one to the right 1.8 m. long, and that to the left 1.2 m. In the main discharge path a contact region of the leader is also observable, and this developed into a loop at a height of 2.4 m. above the surface of the sand. The same type of loop has sometimes been observed in model sparks. The resemblance between the natural lightning and the laboratory discharge is striking.

SOME CONCLUDING REMARKS

It has already been mentioned that some decades ago lightning was regarded as a high-frequency oscillatory discharge, and other out-of-date opinions were still current at that time. It is rather remarkable that such an important field of research should have lagged behind as it did, especially as the results are of considerable practical importance. In future, it is clear that lightning research must lead to problems with far-reaching consequences in electrophysics.

The dilatoriness was due to several factors. As we have seen, a rational approach to lightning research demands a large range of apparatus which is often beyond the resources of the individual worker. The chance nature of lightning's occurrence is another difficulty. It was not until the third year after the installation of the research station in the Empire State Building that satisfactory oscillograms were obtained. An even more striking example is provided by Boys camera; the inventor tried for thirty years in vain to obtain a photograph of lightning with his instrument, and it was not until the 1930's that it gave excellent results in connection with the discharge mechanism of lightning.

The rapid development of electrification during this century was the occasion of a comprehensive investigation of lightning. Transmission lines and installations connected to them were unavoidably exposed to disturbances and damage caused by lightning. This gave rise to problems of quite another order than the comparatively simple ones associated with the protection of buildings.

The new research required a special measuring instrument which must satisfy many demands. It must reproduce without distortion the electromagnetic variations coupled with lightning and its subsidiary phenomena. These variations were such that voltages could rise to millions of volts in millionths of a second. The instrument must also come into action for thousandths of a second as the occasion arose, when the lightning flash swept through involved variations in the space of some few millionths of a second. The modern cathode-ray oscillograph has provided this solution. Without this instrument it would have been impossible to solve the important problems which investigators were compelled to consider. This remarkable instrument well deserves our praise for the precision with which it performs an exceedingly delicate task, and the rapidity with which it records electromagnetic variations. This recording speed has recently, see Park (**51**), attained a value of 230 metres within one millionth of a second or of about three quarters of the velocity of light.

It is well known that the cathode-ray oscillograph has rapidly come to the fore in a number of important fields of research. We need only mention radar, television, ionosphere research, piezoelectric measurement of rapid changes of pressure, and other applications in electronics and atomic research. But it was in lightning research that this instrument first came into its own, and in this field it will always retain its place.

It was thus the cathode-ray oscillograph which made possible the development of modern lightning research along consistent lines. To begin with, the oscillograph revealed the secrets of the variation forms of the lightning discharges and subsidiary phenomena, the lightning surges on electric transmission lines. It then became the indispensable control instrument for various practical applications. In the modern high-tension laboratory it is possible to reproduce lightning discharges in impulse generators for both high voltage and high current, using the cathode-ray oscillograph as a control. Such lightning research can provide us with something more than knowledge of lightning: construction of apparatuses of great practical importance, lightning surge arresters and other protective appliances against lightning.

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ACKNOWLEDGMENTS FOR ILLUSTRATIONS

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NOTES FROM THE FRANKLIN INSTITUTE LABORATORIES FOR RESEARCH AND DEVELOPMENT

A FREEZE-OUT APPARATUS FOR THE COLLECTION OF AIR CONTAMINANTS

The City Planning Commission of Philadelphia, seeking to rejuvenate certain industrial areas in the city, which are blighted by fumes, odors, and other air contaminants, enlisted the services of the Laboratories to obtain technical information that would be used in planning an air pollution control program. Researchers in the Colloids Section of the Chemistry and Physics Division are responsible for the successful development of new techniques and testing devices for investigating air contaminants. Of especial importance is that this work forms the basis for the treatment of odors as air contaminants, an approach hitherto unavailable because legal evidence is lacking that odors *per se* do any harm. If, however, the chemical constituents of offensive odors can be detected and their concentration measured, then their emission can be regulated and a reasonable control plan can be instituted.

The Laboratories have developed a condensing device capable of detecting atmospheric impurities present in minute concentrations, which, coupled with infrared-spectroscopic and microchemical analyses, permit the detection, identification and measurement of the chemicals that, when they are allowed to escape into the air, cause odors. The purpose of this condensing device, or freeze-out train, is to permit the entrapment of analyzable quantities of atmospheric contaminants in a relatively brief period of time. This is achieved by increasing the capacity of a standard freeze-out train, while maintaining a high recovery rate. Thermal efficiency tests indicate that this equipment is capable of cooling as much as 2.5 cubic feet of air per minute to −183° C.

The essential features of the freeze-out apparatus are:

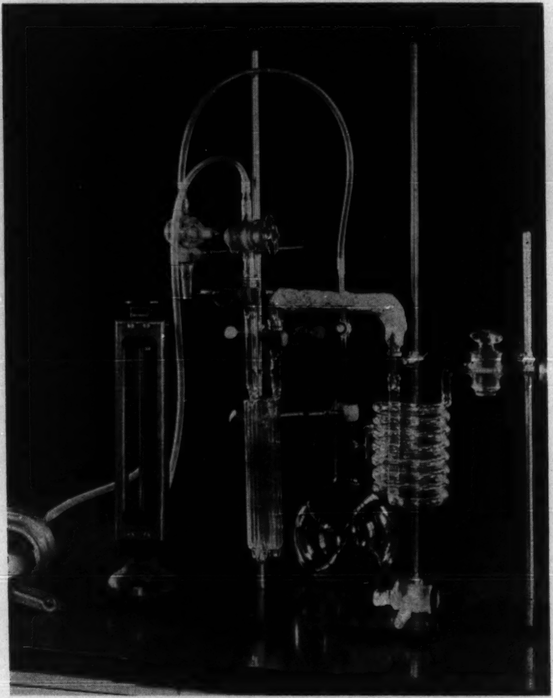
A precooling coil maintained at −72° C. in a CO_2 isopropyl alcohol bath;

A liquid nitrogen condenser consisting of two concentric, hollow-walled cylinders with a total ratio of surface area ($cm.^2$) to volume ($cm.^3$) of six to one, which permits a rapid transfer of heat away from the moving stream of contaminated air;

An evacuated expansion flask to accommodate the increased pressure as the liquid nitrogen trap warms; and

A 300-watt blower capable of producing flow rates of up to 3.5 cubic feet per minute.

Calibration tests using a sample of air contaminated with 200 parts per million of ammonia have shown that this equipment can recover 75 to 90 per cent of the contaminant when the flow rate is one cubic foot per minute, or less. At higher flow rates the efficiency is lower, probably because condensing particles are being swept out with the more rapidly moving air stream.



Laboratory model of the freeze-out apparatus used in the collection of air contaminants.

With the recovery and identification of malodorous impurities thus made possible, a program for controlling the emission of odors can proceed, and many areas that were once blighted by odor and avoided by home-builders or industry can now be reclaimed.

EDMUND THELEN AND SAMUEL N. MUCHNICK

NOTES FROM THE NATIONAL BUREAU OF STANDARDS *

A NEW THEORY ON VHF RADIO WAVE PROPAGATION

A new theory for the propagation of VHF radio waves beyond the horizon has been announced by the National Bureau of Standards. The theory, developed by Dr. J. Feinstein of the NBS staff, not only accounts for VHF and microwave signals that have been observed at distances beyond the horizon but explains the natural and inevitable—as against "unusual" or "accidental"—occurrence of such transmission. The theory has significant practical implications with respect to television and other high-frequency communication services.

The radio waves concerned have a wavelength of around 3 meters or less corresponding to frequencies of 100 megacycles or higher. Their transmission has been referred to as "line-of-sight" or optical because these waves travel largely like light waves in a straight line. This has meant that the general limit of transmission range is just beyond the optical horizon. The over-the-horizon range is determined by the theory that considers the earth's radius—with respect to radio waves—as being 4/3 the actual radius of the earth. This results from bending of the rays in the earth's atmosphere. However, usable signals have been observed well beyond the radio-optical horizon—200 to 400 miles from the transmitter—more often than could be attributed to anomalous conditions in the atmosphere.

Signals far beyond the radio-optical horizon have been explained by previous theories on the basis of unusual meteorological conditions or unusual inhomogeneities in the density of the atmosphere. For example, some investigators have explained the phenomenon by the presence of "ducts" or "channels" in the atmosphere having a density which differs from the air above and below. Such theories have not accounted fully for the regularity of the phenomenon.

The theory developed at NBS suggests a new role for the gradual change in the refractive index of the atmosphere with height. This change, or gradient, leads to reflection as well as refraction of VHF waves as they travel out into space from the transmitter. The amount of reflection is small, but it is enough to lead to appreciable propagation of signals beyond the horizon.

This gradient-reflection theory appears to be corroborated in regard to frequency, angle dependence, range, etc., by NBS experiments and by other research in the field. However, the new ideas are related to

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* Communicated by the Director.

existing theories because all are based on the same fundamental hypothesis. This hypothesis assumes the earth to be a perfectly smooth sphere possessing an atmosphere which gives rise to a refractive index that changes exponentionally with height. Several apparently minor approximations are necessary to adapt the ideal model to the conditions that actually apply. In light of the newer theory, there is a strong suspicion that these approximations have a much larger effect than previously assumed. Thus, efforts are being made at NBS to develop a more complete theory that will justify the approximations or, alternately, to develop a new model that can be relied upon to predict propagation characteristics during any season and under all atmospheric conditions.

Further experimental verification will be sought using new NBS transmitters located at 9000 ft. altitude on Cheyenne Mountain in Colorado and extra-sensitive receiving equipment placed on the gradually sloping plains eastward from the site.

The implications of the NBS theory are many. For example, radio communication at longer ranges than line-of-sight now appears feasible at the VHF frequencies. This increases the possibilities for such communication service as aircraft-to-ground transmission and mobile radio telephony. It means, also, that high-powered TV stations located farther apart than line-of-sight distance will very likely interfere with each other. Thus the problem of allocating television channels will become increasingly complicated.

SPECIFICALLY LABELLED RADIOACTIVE SUGARS

The National Bureau of Standards has developed specifically labelled radioactive sugars. Sugars labelled with radioactive carbon 14 have long been sought by research workers in the fields of biology, medicine, and chemistry. Dr. Horace Isbell, who is in charge of the project for the NBS, has been directing a team of research chemists for the past three years. The work was supported by the Atomic Energy Commission.

Labelled sugars, which are chemically indistinguishable from normal sugars, will be particularly useful in biology where scientists are interested in discovering the mechanism by which a molecule becomes either a source of energy or contributes to the structure of living cells. Because "hot" sugars have an atom of carbon 14 precisely placed in their structure, they can be traced through the complicated chemical reactions vital to animal and plant life.

A typical application in biology is the study of how the body uses lactose, or common milk sugar. Lactose is made up of glucose and galactose. Glucose is the primary source of energy in animal life while the latter substance is an important carbohydrate constituent of brain and nervous tissue.

Animals can be fed radioactive lactose and later be examined to find out where the sugar was utilized. Biologists are interested in knowing whether the galactose found in the nervous system came from the original lactose received through the diet or whether it was manufactured in the body.

In bacteriology scientists are interested in finding out how bacteria react with the simple sugars to produce such complex substances as cellulose. Cellulose is the main constituent of common plants such as trees, corn, and cotton.

Bureau scientists realized the importance such a development would have when they suggested the project to the A.E.C. three years ago. A large portion of the constituents of animal and vegetable life consists of carbohydrates or their derivatives. Carbohydrates are combinations of carbon, hydrogen, and oxygen which vary in complexity from a simple sugar like glucose to high polymers like starch and cellulose. Glucose is a combination of six carbon atoms, twelve hydrogen atoms, and six oxygen atoms. In making the radioactive glucose the number one carbon atom was first removed from the sugar molecule. This left a five carbon sugar known as arabinose. By a complex process having several separate chemical steps, radioactive carbon 14 was then put back into the molecule. This, or a similar method, is used by the Bureau for making various radioactive sugars.

Prior to the NBS project other research workers had attempted the synthesis. They met with limited success. But their yields of radioactive sugar amounted to only 5 to 10 per cent of the original carbon 14. The yields obtained at the Bureau have ranged from 40 to 60 per cent.

Earlier workers also made radioactive sugars using a biological process. However, the "hot" atoms were randomly distributed throughout the sugar molecule. Though these sugars were useful, scientists realized that a molecule labelled in one known position only would serve more useful purposes.

A substantial number of different position-labelled sugars have now been made available by the Bureau. They are being purchased by private and governmental laboratories as fast as they can be produced. The cost of the radioactive sugars is about $1000 per gram or $28,000 per ounce. Laboratories seldom need amounts even as large as a gram however, because the sugars can be greatly diluted without losing their effectiveness as a tracer compound. The largest single amount supplied to date has been one-quarter gram.

FILM READER FOR TELEMETERED INFORMATION

A semi-automatic film-reader system recently developed at the National Bureau of Standards for the Navy Bureau of Aeronautics, facilitates the transcription of telemetered information recorded on 16-millimeter film. The new film reader was developed by F. H.

Bayhi and M. L. Greenough of the NBS electronic instrumentation laboratory for operation in conjunction with the NBS parachute-telemetering system, in studying the behavior of military parachutes in test drops.

The NBS parachute-telemetering system is designed to transmit, from a parachute-borne radio transmitter to a ground station, information needed in studies of parachute performance—altitude, forces at various points, and similar data. The transmitter is modulated by a calibration signal and up to seven measurement signals, selected in turn by a commutator device. On the ground, a receiver demodulates the transmitted information and feeds it to a cathode-ray tube. A single spot on the face of the tube moves up and down with the amplitude of the transmitted measurements, and its position is recorded continuously on film moving at constant speed. This gives a series of pulses on the film, with peaks of varying height, the height of each peak corresponding to a single measurement.

The observations are made at the rate of 6000 sets (commutator revolutions) per minute, but are made continuously only during certain critical portions of the parachute's fall. A typical film record of a single parachute drop depicts about 500 sets of measurements, made at successive intervals of time, each set consisting of a single observation of each of eight quantities (one set per commutator revolution). To make it useful, the data on the film must be replotted to give 7 curves (the calibration signal is omitted) having a common time scale, each showing one of the measured quantities as a function of time. This is the problem that the NBS film-reader system was developed to handle.

In the new film-reader the enlarged image of a set of measurements is projected onto a horizontal surface; mechanical marker tips connected to potentiometers are manually adjusted to coincide with the peaks and base-line of the projected film image; and voltages derived from the potentiometers are fed to a modified commercial strip-chart recording instrument having an eight-channel input.

Seventeen of the signal-measurement potentiometers are used, one for each of the eight film-image peaks and one for the baseline point on either side of each peak. The potentiometers associated with each channel are connected in a network to which d-c. voltage is supplied, and the arrangement is such as to give across one of the network summation resistors a d-c. voltage proportional to the amplitude of the corresponding signal image on the film.

After setting the marker tips on the image of the first set of eight measurements, the operator adjusts the sensitivity of the system so that the calibration signal is set at a standard level. He then presses a button that puts the recorder through an automatic printing cycle. In each cycle the recorder selects one after another of the eight measurement channels and—as soon as balance is achieved—prints the measured value of special chart paper marked off into seven equal-width strips. Instead of the regular slow-speed continuous chart-drive, the driving mechanism is arranged to advance the chart approximately 0.005 in. each time the recorder prints.

After printing a value for each channel, the recorder stops automatically. While the recorder is printing, the operator advances the film to the next set of measurements. He now again aligns the marker tips connected to the signal-measurement potentiometers and presses the button to start the recorder through a new cycle. The process is repeated until all sets of measurements for the particular parachute drop have been thus transcribed from the film to the chart.

To make the recorder print properly in the seven separate strips on the recorder chart, separate bias voltages are inserted automatically for channels 2 through 7. No bias is needed for channel 1, as its zero point is also the zero point of the recorder pen.

Telemetered film records of a great many parachute drops must be studied in the research program for which the NBS parachute-telemetering system was developed, and the new film reader makes possible important savings of time as well as greater freedom from error in transcription. In the past, an operator using a simple microfilm viewer and scale has required about three days to take from the film strip the data for a single parachute drop, and the data have then had to be plotted by hand. Using the new film reader, the entire operation is expected to take only three or four hours. Since no mental interpolation is required, operator fatigue is also reduced. With clear film images and careful alignment of the marker tips, total error is well under 5 per cent. Since variation among individual parachute drops is considerably greater, the errors in the film reader are relatively small.

THE FRANKLIN INSTITUTE

MINUTES OF THE STATED MEETING

April 16, 1952

The Stated Monthly Meeting of The Franklin Institute was held on April 16, 1952, in the Lecture Hall of The Franklin Institute. S. Wyman Rolph, President, called the meeting to order at 8:15 P.M. Approximately 375 persons attended.

The President stated that the Minutes of the Stated Monthly Meeting in February were printed in full in the March issue of the JOURNAL; there being no corrections or additions, they were approved as printed. The Minutes of the Stated Monthly Meeting in March are being printed in the April issue of the JOURNAL and will be submitted for approval next month.

The Secretary reported the following elections to membership for the month of March:

Active	38
Associate	33
Student	15

and a total Institute membership of 6,319 as of March 31, 1952.

He drew attention to the dramatic and spectacular presentation "Creation of the Universe" which will be shown in the Planetarium during April and May. He invited Institute members to a special private tour of "Science Fair" on April 30th following an informal buffet supper sponsored by the Membership Department. "Science Fair," sponsored by the *Philadelphia Inquirer*, will be held in Franklin Hall from April 26th to May 4th and is designed to promote interest in science and the crafts among local students in our ten-county area. Institute members were also invited to a joint meeting with the Philadelphia Science Teachers' Association on May 7th, at which the guest speaker will be Mr. H. P. Adams, Meteorologist in charge of the Philadelphia Weather Bureau.

The President then welcomed the officers and members of The Rittenhouse Astronomical Society to this Joint Meeting with The Franklin Institute. After a few introductory remarks about the Society, Mr. Rolph presented its President, Professor Frank Bradshaw Wood, who took the chair. Professor Wood introduced the speaker for the evening—Dr. Gerard P. Kuiper of the Yerkes Observatory, University of Chicago.

The essentials of Dr. Kuiper's interesting illustrated lecture will be printed in a future issue of the JOURNAL.

Following a question-and-answer period, the meeting adjourned at 10:00 p.m. with a rising vote of thanks to Dr. Kuiper.

HENRY B. ALLEN
Secretary

COMMITTEE ON SCIENCE AND THE ARTS

(Abstract of Proceedings of Stated Meeting held Wednesday, April 9, 1952.)

HALL OF THE COMMITTEE,
PHILADELPHIA, APRIL 9, 1952.

MR. HOWARD STOERTZ in the Chair.

The following report was presented for final action:

No. 3241: Work of H. Birchard Taylor.

This report recommended the award of an Elliott Cresson Medal to H. Birchard Taylor, of Philadelphia, Pennsylvania, "In consideration of his inspiring leadership in the development of the single runner vertical reaction turbine, his many patents and his contributions to technical literature."

JOHN FRAZER,
Secretary to Committee

MEMBERSHIP

ACTIVE MEMBERS ELECTED AT THE MEETING OF THE BOARD OF MANAGERS

April 16, 1952

ACTIVE FAMILY

M. John Boyd, Ph.D.
William J. Gordon
Walter W. Miller
L. O. Veith
Walter T. Whitehead

ACTIVE

Richard G. Alexander
William Philip Blessington
Walter Chism
James K. Coyne
William Craemer
Palmer M. Craig
John D. Crawford
Frank G. Deker
John T. Fisher, Sr.
F. C. Gladeck, Jr.
J. Edward Godwin
A. Kenneth Graham, Ph.D.
Lee S. Harris, Jr.
Hiram E. Hollings
Almern C. Howard
Comdr. H. J. Huester
Guy Lincoln Huey
Felton S. Jenkins, Ph.D.
Hess Kline
Edward C. Kradoska
James A. McGuigan
Joseph F. Meister
Philip A. Pizzi
R. H. Pruitt
Howard W. Robinson, Ph.D.
Robert F. Schmidt
Alex F. Schoemann
James G. Stewart
Stanley F. Ward
G. Donald Whyte

ACTIVE NON-RESIDENT

John S. Beattie

NECROLOGY

Walton Forstall '07
Morris E. Leeds '97
Heyman Rosenberg '30
Harry Stuckert, M.D. '45

MUSEUM

Two hundred and fifty years ago, in the early days of the "Holy Experiment," the great ore beds, the thickly wooded country furnishing charcoal in plenty, and the strong streams promising abundant water power, impelled many capable and hopeful men to attempt the making of iron in Pennsylvania. Before the time of Penn's arrival the groups of settlers along the banks of the Delaware do not appear to have made any effort to manufacture iron goods. Owning iron furnaces in Hawkhurst, England, Penn not unnaturally wished to encourage its production in his own province. Although he had no connection with any of the efforts actually made at iron making, he was acutely conscious of the opportunities, for in 1683 he wrote of "Mineral iron and copper in various places." During his later years he was begging his secretary Logan to investigate the mineral resources of the province in the hope that the development of iron mines and furnaces might relieve him of his financial embarrassments.

The first successful attempt to make iron in the province appears to have been made by Thomas Rutter in 1716, when he constructed the Pool Forge on Manatawny Creek, about three miles above Pottstown. This was a bloomary of the Catalan type which had been developed in Spain about the tenth century. Rutter was also responsible for building the first blast furnace at Colebrookdale. The Coventry Forge, on French Creek was established in 1718 or 1719 by Samuel Nutt, and here steel was made for the first time in America.

In these very early furnaces two and a half tons of ore and 180 bushels of charcoal produced about one ton of iron. Most of the furnaces made stoves, firebacks, kettles, pots, sash weights, and similar small castings.

During the next hundred years the manufacture of iron and steel made great strides, as may be seen from a fine model of a rolling mill which has been added to the Museum. The original of this mill was situated on the west branch of the Brandywine River, south of Coatesville. The history of the Old Mill is shrouded in mystery but the details of its interior were preserved in an engraving which decorated the back of a banknote issued by a Chester bank. The scene depicts the interior of a typical rolling mill as they existed prior to the Civil War.

The model shows two wood-fuel furnaces, a rolling press, and shears. The press and shears are operated by water power. The overhead gear for handling billets, hot metal, rolled sheets, etc. is complete. Everything is constructed to exact scale and with the utmost fidelity to the practice of the times. All the operating parts can be operated by turning the water wheel. Although some of the finer details cannot be demonstrated to Museum visitors, the model has been so accurately constructed that all the parts which should move have been made movable.

The model was built by Mr. F. M. Beltrando, Coatesville, who has placed it on indefinite loan in the Museum, where it will form a valuable introductory step to the story of modern steel making which is being prepared on an extensive scale, and which will be a conspicuous addition to the major Museum exhibits in the near future.

JOURNAL OF THE FRANKLIN INSTITUTE

The following papers will appear in this JOURNAL within the next few months:

MOON, PARRY AND DOMINA EBERLE SPENCER: Separability Conditions for the Laplace and Helmholtz Equations.

BISPLINGHOFF, R. L. AND C. S. DOHERTY: Some Studies of the Impact of Vee Wedges on a Water Surface.

SAIBEL, EDWARD: Buckling of Continuous Beams on Elastic Supports.

RYDER, FREDERICK L.: Network Analysis by Least Power Theorems.

MINORSKY, N.: Stationary Solutions of Certain Nonlinear Differential Equations.

TOMOVICH, RAJKO: A Universal Unit for the Electrical Differential Analyzer.

SHAW, M. C.: A Yield Criterion for Ductile Metals Based Upon Atomic Structure.

BURROWS, W. H.: Some Properties of Hyperbolic Coordinate Systems.

SILBERSTEIN, L.: Properties of an Exponential Size-Frequency Distribution of Finite Extent.

POLNAUER, FREDERICK F.: Bio-Mechanics—A New Approach to Music Education.

LIBRARY

The Committee on Library desires to add to the collections any technical works that members may wish to contribute. Contributions will be gratefully acknowledged and placed in the library. Duplicates received will be transferred to other libraries as gifts of the donor.

Photostat Service. Photostat prints of any material in the collections can be supplied on request.

The Library and reading room are open on Mondays, Tuesdays, Fridays and Saturdays from 9 A.M. until 5 P.M.; Wednesdays and Thursdays from 2 P.M. until 10 P.M.

On and after June 1, the Library hours will be 9 A.M. until 5 P.M. on Mondays, Tuesdays, Wednesdays, and Fridays; 2 P.M. until 10 P.M. on Thursdays; and 9 A.M. until 12 noon on Saturdays.

RECENT ADDITIONS

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BOOK REVIEWS

FINITE DEFORMATIONS OF AN ELASTIC SOLID, by Francis D. Murnaghan. 140 pages, 15 × 23 cm. New York, John Wiley & Sons, Inc., 1951. Price, $4.00.

The classical treatment of the theory of elasticity is based on the assumption of infinitesimal strains, an assumption which is satisfactory in most cases for engineering purposes provided the material is stressed within limits such that plastic flow or fracture does not occur. However, there are cases in which the assumption of infinitesimal strains does not apply with sufficient accuracy even where the loading is elastic. Such cases include materials loaded under high hydrostatic pressures where elastic deformation takes place even up to relatively large strains; also deformations of rubber and other materials having low elastic moduli may fall in this category. To obtain satisfactory results in such cases it is necessary to discard the assumption of infinitesimal strain and in general this greatly increases the complexity of the problem, although the results may be obtained in a fairly simple form for certain special cases.

In this book, which is based in part on lectures given to various technical institutes, Professor Murnaghan, who is widely known for his contributions to the subject of finite elastic deformations, treats this difficult problem by using matrix methods exclusively, thereby achieving a high degree of compactness in the formulas. The problem is thus treated more from the viewpoint of the mathematician than from that of the engineer. For example, the author states in the first sentence of the book that "the theory of finite deformations of an elastic solid is most easily presented and understood by the use of matrices." While this statement may well apply to mathematicians and others familiar with matrix theory, it seems doubtful whether it also applies to most engineers who are not familiar with such methods and who in addition are accustomed to looking at the physical picture rather than the mathematics involved. Although the reviewer, being an engineer, may be prejudiced in this regard, it would seem that the advantages obtained by using matrix methods have been secured at the expense of making the book more difficult reading for the large majority of engineers and others interested primarily in applications. As far as the purpose of the book is concerned this is probably not a serious disadvantage, since the book appears to be written primarily for use as a textbook, judging from the many problems given and from the frequent use of parenthetical expressions such as "why" or "prove this" interspersed throughout the text. In this connection, the author apparently realizes that many readers will have difficulty with the matrix treatment since he devotes the first chapter entirely to an exposition of the elements of matrix theory which are necessary for an understanding of the subject. In addition he admonishes his readers not to "fall into the error of regarding (matrices) as a complicated device invented by mathematicians to make the theory of elasticity harder than it actually is."

Coming now to a discussion of subjects and methods of treatment, Professor Murnaghan first deals with the strain matrix, transformations of coordinate reference frames, strain invariants and compatability relations. He then goes on to treat the stress matrix, conditions of equilibrium, elastic energy, boundary conditions, and relation between stress and strain. The treatment is somewhat unusual in that, using the principle of virtual work, an expression is obtained for the stress matrix involving the partial derivative of the energy of deformation with respect to the strain matrix. This expression also involves the Jacobian matrix J and its transpose J^*, where $J = (x, y, z)/(a, b, c)$. x, y, z are the final coordinates of a particle and a, b, c are the initial coordinates. The strain matrix is defined as $\frac{1}{2}(J^*J - E_3)$, where E_3 is the unit matrix.

After deriving general expressions in matrix form, the author then proceeds to apply the results to particular cases. For isotropic media, it is assumed that the energy of deformation may be developed into a power series of the strain invariants. By considering infinitesimals of higher orders in this series, more exact expressions are obtained. Thus the following particular cases are treated: scalar strain (hydrostatic pressure or tension); simple shear; simple tension; spherical shell under pressure; circular tube under pressure; cylinder in torsion.

Considerable space is devoted to the case of hydrostatic pressure, and the author shows remarkably close agreement between his calculated results (using either the integrated linear theory or the second-order approximation) and the test results of Bridgman obtained on the metal sodium at pressures up to 10^5 atmospheres. For such high pressures, as would be expected, the results obtained by classical elastic theory based on infinitesimal strains are greatly in error.

Non-isotropic elastic media are also discussed with particular reference to crystalline media, and it is emphasized that an applied stress may make an initially isotropic medium into a non-isotropic one.

The author also applies the formula for the case of scalar strain (integrated linear theory) to the calculation of *rupture* under hydrostatic *tension* using experimental constants determined from Bridgman's hydrostatic pressure tests. Although this is no doubt an interesting calculation, the reviewer feels that the phenomenon of rupture is such a complicated one, involving so many physical factors, that it is unlikely that significant quantitative results will be obtained by using elastic theory alone.

Likewise, the author on page 115, referring to "simple tension" states that "the extended linear theory is capable of explaining the phenomenon of flow of a cylinder under tension; but in order for it to do so one must take into account the dependence of the elastic constants on the applied tension." Presumably the word "flow" here refers to the plastic flow which ordinarily occurs in tension tests of metals where cylindrical bars are loaded to fracture. If this is the author's meaning, it does not seem justifiable to apply elastic theory to a process which is essentially non-elastic and irreversible. On the other hand, it appears that the theory may explain the curved stress-strain diagrams of materials like rubber when not loaded beyond the point where appreciable plastic flow occurs.

Other features of this book which, to engineers, might be considered as detracting somewhat from its usefulness are: lack of a numbering system for important equations; lack of any figures or illustrations which might be helpful in certain cases in understanding the argument or in obtaining a better physical picture of what occurs; omission of references to other treatments of the subject available in the literature; symbols for stress, strain and elastic constants different from those most commonly used in engineering work in this country. However, it may be that from the standpoint of the use of the book for teaching purposes or by applied mathematicians, these defects are of no great importance.

Professor Murnaghan is to be congratulated on the production of an authoritative and scholarly treatise on a difficult subject. He states in the preface "If the mathematical treatment given here serves to stimulate the procurement of experimental knowledge of these phenomena, we shall have attained our aim." In this connection the reviewer believes that there are distinct possibilities in the application of the methods developed, when used in connection with further experimental work, for obtaining a better understanding of the phenomena involved.

A. M. WAHL

THE FLIGHT OF THUNDERBOLTS, by B. F. J. Schonland. 152 pages, 15 × 23 cm. Oxford, The Clarendon Press; New York, Oxford University Press, 1950. Price, $3.00.

According to Priestley's account of the incident, Benjamin Franklin performed his famous kite experiment in June, 1752. While that may establish a convenient date for the beginning of an understanding it was by no means the beginning of the observation of this manifestation of nature. Dr. Schonland, of the University of the Witwatersrand, in this fascinating book delves deeply into the recorded history of lightning and finds that it has always and everywhere been watched with a great deal of interest and awe. He has collected a surprising number of recorded incidents in which ships at sea and property on land were damaged by lightning strokes. But it is not to be supposed that his book is a mere collection of historical episodes. It is by far the most comprehensive study of lightning that has come to our attention. Written with engaging simplicity it will appeal to the general reader and to the specialist.

There is an interesting chapter on the work of Franklin which assembles his frequent allusions to the experiments with lightning, and which makes a careful evaluation of Franklin's contribution to the subject. This is followed by an illuminating chapter on what might be called the natural history of lightning, dealing with its forms, colors, and habits. A description of the Boys camera follows, with an account of the characteristic forms, the pilot, the stepped leader, the dart, and the return streamers—the four main processes in the lightning discharge—which were detected with the aid of this ingenious device. These are processes which can be studied only through the light emitted by the discharge, and the fundamental electrical processes are reserved for description in a subsequent chapter which is one of the best in the book.

The correct construction of lightning protection receives adequate treatment and there is an interesting comment upon the still unsolved problem of the protective radius of a single rod. The vexed question of points or knobs is left in suspense, since Dr. Schonland says the lightning rod may have either a pointed or a blunt end. The final chapters will be of special interest to meteorologists.

Although Dr. Schonland has made his investigations in South Africa he ranges far and wide over the face of the earth for illustrations to support his conclusions, and he has peered with acute perception into every nook and cranny of his field. No technical language is employed, so that the general reader may accompany the physicist, the electrical engineer, and the meteorologist on a voyage of discovery into a subject which hitherto has not received the attention it merits.

The visual observation of the lightning flash is apt to lead to confusion and misconceptions because the brilliance of the main channel of the discharge dazzles the observer. The reader of this book will have no difficulty whatever in forming a clear perception of the growth of the electrical charge in a cloud, the discharge of the multiple regions, and the subsequent course of the flash in its varying forms. The problems confronting the author were difficult and complicated, but his investigations have been so thorough and his understanding of the various manifestations appears so complete that he is able to present an explanation of lightning that reads as though it were a very simple process; certainly he makes it easily comprehensible. It is a book that should be read by all physicists, electrical engineers, and meteorologists, but those who will derive most satisfaction from it are those general readers who still retain a curiosity about the ways of nature.

T. C.

WAVEGUIDE HANDBOOK, edited by N. Marcuvitz. 428 pages, tables and illustrations, 15 × 23 cm. New York, McGraw-Hill Book Co., Inc., 1951. Price, $7.50.

Waveguides have seen practical application for barely more than a decade, because their use has naturally coincided with the adaptations of microwaves. Waveguides are the logical circuit elements for conveying microwaves. They are more efficient than the coaxial cable, and in the centimeter wavelengths can be made conveniently small in size. Today catalogs of commercial firms show for sale a large variety of waveguides and waveguide accessories; in 1944 all waveguide assemblies were made to order; in 1939 only a few university staff members and industrial researchers had ever seen a waveguide, and this they had made themselves. It is interesting to see how knowledge of this subject spread and was published in various forms, including most recently the "Waveguide Handbook" which we are considering.

The most significant initial investigations dealing specifically with waveguides as we now know them were published by W. L. Barrow of the Massachusetts Institute of Technology in 1936 and simultaneously by Southworth at the Bell Telephone Laboratories. The first books on waveguides were published in the early 1940's under military secrecy, with the exception of a general treatise on the theoretical aspects of microwave transmission by J. C. Slater. Notable among the confidential books was "Microwave Transmission Design Data," prepared by the Sperry Gyroscope Company in 1944. Some of these books are cited because they contain as much waveguide information in handbook form as the volume being reviewed.

The above may seem to imply that the new Volume 10 of the Radiation Laboratory series is not a valuable book on certain aspects of waveguide theory. However, that implication is not intended, for this is the first extensive attempt at reducing waveguide theory and practice to a basis of network relations. The book is devoted to derivations of susceptance, impedance, admittance and other characteristics of waveguide elements. In this the book has no equal.

The name "Handbook" will be misleading to many because one expects to find a broad coverage of the subject in readily applicable form. To obtain this coverage of waveguides one would need to add Volume 9, "Microwave Transmission Circuits," as well as the Sperry book, and several others. The index in this book is very brief and is not helpful in finding information on many specific items. In some ways it is not as polished editorially as the other volumes, using unexplained statements such as, "These data are quite old and are not of high accuracy."

From an engineering viewpoint the data in this book are presented in a reversed form. That is, one usually would like to know the physical dimensions to achieve certain desired electrical characteristics. The derivations in the book are expressed so that the electrical characteristics are computed from given physical dimensions, which one does not have when developing new components. It therefore appears to be written from the viewpoint of one trying to explain the performance of an existing waveguide configuration rather than the engineer who contemplates an original design and desires to set down the unknown dimensions. However, the work presented makes the rewriting of the derivations into convenient form an easy matter, so that this objection does not detract greatly from the book's value to the engineer. The use of the volume for teaching waveguide principles should also prove very successful.

C. W. HARGENS

D-C. POWER SYSTEMS FOR AIRCRAFT, by R. H. Kaufmann and H. J. Finison. 206 pages, illustrations, 15 × 24 cm. New York, John Wiley & Sons, Inc., 1952. Price, $5.00.

"This book is one of a series written by General Electric authors for the advancement of engineering practice." It specifically relates to electrical power systems installed in aircraft.

Characteristics of power sources and control equipment are discussed in detail and the way these characteristics affect the behavior of the system as a whole is thoroughly treated. The design of the systems using various types of equipment and various regulating and protective equipment is explained. Some mathematical analysis is used in this explanation but in general the detailed mathematics is omitted or relegated to an appendix. This makes the material easier to read. Numerous charts and graphs based on test data and numerous references also are designed to help the reader. The majority of references are to material published before 1945 when the authors were working full time in the field.

Power systems for aircraft must meet many special and severe requirements. Temperature extremes, humidity, vibration, and shock are present in all aircraft operation. And on these are imposed the extreme variations in prime mover speed, necessity for complete reliability, ruggedness, small size, and light weight. These problems make system design difficult and reliable control equipment necessary. The wealth of practical information based on first hand experience and tests makes the information in this book valuable to the engineer or designer working on aircraft power systems.

E. A. MECHLER

CEREBRAL MECHANISMS IN BEHAVIOR: THE HIXON SYMPOSIUM, edited by Lloyd A. Jeffress. 311 pages, illustrations, 15 × 24 cm. New York, John Wiley & Sons, Inc., 1951. Price, $6.50.

The symposium on which this book was based was held for the purpose of bringing together leaders in various scholarly disciplines in order to break down some of the shadowy barriers between related life science studies and to extend the periphery of knowledge. In general the symposium would mainly interest a psychologist or neurologist, except for the fact that a certain emphasis was placed on analogies between neural action and large scale computing machines. Dr. J. Von Neumann set the stage for this type of discussion by presenting a general and logical theory of automata, and Dr. W. S. McCullock followed with a more specific theory which hoped to describe cerebral functioning. These two talks and the related discussions should be quite fascinating for a mathematician, a physicist, or perhaps an electrical engineer who is interested in the applicabilities of mathematical models to a problem as fantastically complicated as the working of the nervous system. The sparsity of conclusive data which results from the inadequacy of present day experimental techniques and available theoretical schemes, results in placing the heart of the symposium in the discussion periods. All in all, the symposium proceedings provide a stimulating and enjoyable reading experience.

EZRA KRENDEL

GENERAL SCIENCE IN EDUCATION, edited by I. Bernard Cohen and Fletcher G. Watson. 217 pages, 15 × 22 cm. Cambridge, Harvard University Press, 1952. Price, $4.00.

Six years ago a report of the Harvard Committee, entitled "General Education in a Free Society," directed attention to the neglect of the science studies in general education. This report started an accelerating development in the colleges and junior colleges across the country. The present volume is a collection of papers in which are discussed the best methods of approaching the subject and evaluating the results. Since the contributors, with a single exception, are well known educators, it goes without saying that the book's contents furnish an important contribution to this aspect of general education. As might be surmized, there is a uniformity of view upon the wisdom of furnishing the layman with an understanding of science and scientific methods which does not conceal some divergence of view upon the goal and the methods to be employed. What provides cause for gratification is the broad field of agreement, for the differences of opinion, where they exist, are of the minor order.

The papers are comprehensive, dealing with science for the non-scientist, philosophy of science and the teaching of science, the history of science, science in a technical civilization, and problems in teaching biology.

The reader does not get far into the volume before encountering phrases that grip the attention, such as this: "Any program aimed at fostering a general interest in science among the public at large must recognize that we have no right to expect others to be interested in the tricks of our specialized trades. We must learn to present to the public those aspects of our activities that possess broad human values." For the value of science lies less in the provision of new gadgets and ultimately new goods than it does in the degree it enriches life with new aesthetic and emotional experience, with broader understanding, and with stimulating mental experiences. The study of science should enable us to recapture some of the wonder of the universe which existed before the scientist abandoned the hope of solving the riddle of the universe by experimental science. The men who express their views in this book appear to be impressed with the conviction that it is of greater importance to the college student to try to understand the world than merely to do things with science. It is their aim to prepare the citizen, as well as the scientist, to be ever ready to change, to adapt himself to a new and, we hope, a better world.

To preserve in our technical civilization the heritage of a political democracy that was nurtured in an agrarian and handcraft economy, we must cultivate a breadth of common understanding that will surmount the barriers of divided labors and group interests. It is encouraging to find a group of eminent educators awake to the realization of the college student's needs, and expressing concern about the best means of satisfying them.

The book can be highly recommended to everyone interested in science: it should be compulsory reading for everyone occupied in teaching science.

T. C.

FUNDAMENTALS OF AUTOMATIC CONTROL, by G. H. Farrington. 285 pages, illustrations, 14 × 22 cm. New York, John Wiley & Sons, Inc., 1951. Price, $5.00.

Within the past decade, there has been a decided increase in the utilization of automatic devices. This broadening has necessitated the development of new techniques to cope with the new demands placed on the art. Considerable amounts of information have been compiled and published on the detailed treatments given to the problems peculiar to this subject. Novel among the works in this collection is this particular book. Among the points of consideration in this volume is that of the lag that invariably exists between the controller and the controlled conditions.

The underlying treatment throughout the entire text is the similarity that exists between plants, processes, and machines involved in control applications, and the fact that they can be simulated by linear electric networks. Heavisides' unit function and the Nyquist stability diagrams are the tools that are used to measure the quality of the combinations of elements under a given set of conditions.

Throughout the book, the author creates a better understanding of the intricacies of a control system. After a brief review of the role of the controller, individual attention is given to each of the basic types and combinations of controls as applied to "feed-back" systems. They are compared on the basis of the relative performance that might be anticipated from each.

Transfer stages are treated by analogus cases; that is, electrical circuits are used to examine the individual responses of pneumatic, mechanical and hydraulic systems to a given control action. Multiple stage combinations are treated to depict the effect of combinations on the stability of the system.

Consideration is given to the lumped parameters and the limitations placed on them by the type of system plus the type of control employed in the system. This is done in an effort to attenuate the wide field of possible combinations of parameters that can be present.

An all inclusive treatment of the variances that can exist either in the supply to, or the demand from, a system is presented in a readily comprehensible manner. It is noteworthy that this portion of the text is handled in a fashion which does not digress from the pattern of understanding set down in the beginning of the book.

To round out the discussion, there is a chapter which deals with the systems that are comprised of more than one loop or more than one means of control.

The last two chapters cover all the preceding work by furnishing an "earthy" application of the theoretical material presented.

"Fundamentals" is a clear exposition of the subject; there is a logical sequence in the presentation of the material. The book is free from obscure statements and trimmings that are usually associated with one of this type.

T. J. BOWDEN

INTRODUCTION TO GEOPHYSICAL PROSPECTING, by Milton B. Dobrin. 435 pages, illustrations, 16 × 24 cm. New York, McGraw-Hill Book Co., Inc., 1952. Price, $7.00.

The necessity for meeting the ever increasing demand for more and more oil has probably contributed more than any other single factor to the development of geophysical prospecting—the means of locating quickly and economically new sources of petroleum. Of course, geophysical prospecting is concerned with the location of minerals and other hydrocarbons beneath the earth's crust, too; but petroleum is by far the most important. Mr. Dobrin, of the Magnolia Petroleum Company, describes all the current, and some of the past, methods of geophysical prospecting. Purposely avoiding any calculus and using nothing more complicated than trigonometry, Mr. Dobrin has written a book on geophysical prospecting that, because of its elementary and descriptive approach, should have a wide audience. As he emphasizes, it should appeal to the neophyte, the advanced student, the professional geologist, and the professional geophysicist.

Technically, geophysical prospecting is the location of hydrocarbon or mineral deposits beneath the earth's crust by means of instruments on the surface. Following an introduction, the author describes the various methods: gravity prospecting, magnetic prospecting, seismic prospecting, electrical methods of prospecting for radioactive mineral, geophysical well-logging methods, and radio and radar prospecting. Each method is approached in much the same way. Generally, the basic principles, instrumentation, field techniques, reduction and interpretation of field data are successively discussed. The inclusion of actual field data and, in many cases, the explanation of case histories greatly increase the practical value of the book. Nothing so effectively illustrates a method nor makes it more understandable, than actual, practical applications. The limitations and most likely use of each method are also discussed.

Photographs and numerous diagrams throughout the book aid materially in the understanding of the text. Although intentionally brief because of the elementary character of the book, the bibliography is nevertheless substantial and should help the industrious reader in his quest for more information.

E. W. HAMMER, JR.

THE PRINCIPLES OF GENERAL BIOLOGY, by Mary S. Gardiner. 657 pages, illustrations, 19 × 27 cm. New York, The Macmillan Co., 1952. Price, $8.25.

"The Principles of General Biology" has been written with the author's avowed intention of providing for liberal arts students and science majors alike an enumeration of the principles which underlie biological thought and method, plus a good general picture of the subject. A departure from the usual first year college biology textbook, this book has been created to serve as a supplement to the information gained by the student in his classroom and laboratory work, rather than as a text of daily lecture material.

Drawing upon the vast experience she has gained in over twenty years of teaching college biology, Dr. Gardiner has placed emphasis throughout the book on the careful development of facts and ideas which she has found to be of particular interest or bafflement to the majority of first year biology students.

The material of the book is presented in four major subdivisions. The first section is devoted to a presentation of the concepts of physics and chemistry which are necessary to a good basic understanding of biological functioning. Section Two contains a treatment of the organization of biological systems. A change from the conventional method here is the discussion of plant and animal life together. Rather than adhere to the traditional sharp distinction between botany and zoology, the author has presented this comparative treatment in order to emphasize the unity of living things and point out the evolutionary development of modern species.

Section Three, "The Operation of Biological Systems," treats in some detail the many aspects of growth, nutrition, and reproduction. The final section of the book is devoted to the derivation of the doctrine of evolution, considered by Dr. Gardiner as probably biology's greatest contribution to human thought.

The painstaking manner in which the author has traced the historical development of many of today's biological facts and theories, for example the vitamin and hormone concepts, the workings of the circulatory system, and the evolution doctrine, should prove especially valuable in aiding the interested student to grasp not only the particular idea or concept under consideration, but also a strong understanding of the workings of the scientific method in general. The many wisely chosen photographs and diagrams included should also be of great help in clarifying the information presented.

"The Principles of General Biology" is recommended as a valuable addition for all college libraries, since it will serve so well the requirements of both the potential scientist and the arts student seeking a basic understanding of this science which so vitally concerns us all as living creatures.

JEAN A. MINKIN

THE AMERICAN ECONOMY, by A. J. Youngsen Brown. 208 pages, 15 × 22 cm. New York, Library Publishers, Inc., 1952. Price, $4.75.

Business in America in more senses than one is everybody's business, to its own great advantage. The man who is engaged in business or in the technology which furnishes the material foundation for business enterprises cannot afford to be without a knowledge of the economic history of the country. The periodic recurrence of financial depressions proves that we are not yet the masters of our national economy, and a good start in acquiring such a mastery can be obtained by a more general understanding of the past and its lingering points of impact upon the present. Economic histories, for the most part, are deadly dull reading, but here is one which can be read with profit and pleasure.

The author is an Englishman who knows American history and has a deep knowledge of economics which he holds in restraint. He views "the American scene" from a detached but not unsympathetic standpoint. Modestly claiming to be no more than a brief but comprehensive account of American economy from the Civil War to 1940, it is a stimulating and, at times, a provocative book, trenchant in its analysis and verging on brilliance in some of its judgments. Naturally, within such short compass little attention can be devoted to detail, but the result is that the reader rarely finds his view of the wood obscured by the trees. In broad outline the salient features of economic history are depicted in bold strokes: the growth of the railroads; the development of industry; banking, investment, and speculation; trusts and government; the depression and the New Deal, and the other major influences which have changed American attitudes during the period of study are treated with skill and understanding.

Because of his viewpoint the author approaches his problem in a manner which is objective and unconventional to American eyes. For example, he makes short work of the "Frontier" school of historians. Some of his views will doubtless come as something of a shock to those who complacently accept the theory of a self-sufficient American economy, but no one can doubt the author's ability to differentiate between the significant and the insignificant factors in his argument. He has dealt with the significant in a manner that is rewarding to the reader who wishes to obtain an over-all picture not over-burdened with detail. Some of the chapters are highly stimulating reading, notably the first (which deals with the peopling of America) and the last, on the American way of life—which is also controversial.

The book has some slight blemishes which could have been corrected by more alert proofreading. Joseph Priestley did not accept a professorship in Philadelphia (p. 15); he rejected the offer. Uninformed readers will carry away an altogether exaggerated view of the territory served by the infant American railroads when the modest Camden and Amboy R.R. is referred to as the "Canadian and Amboy R.R." (p. 34). But these flaws do not mar an admirable piece of work.

T. C.

BOOK NOTES

STANDARD TIME IN AMERICA, by John S. Allen. 20 pages, 15 × 23 cm. New York, National Railway Publication Company, 1951. Paper.

Although small, this pamphlet describes in detail the facts leading up to the adoption, in 1883, of Standard Time in America. It gives background material on prior methods of timekeeping and describes the difficulties involved in trying to run railroads on schedule, when more than 50 different times were in use. The ultimate adoption of the plan was due largely to the efforts (set forth in detail in the pamphlet) of William F. Allen, Secretary of the Time Conventions in 1883.

THERMODYNAMICS, by George A. Hawkins. Second edition, 563 pages, diagrams, 14 × 22 cm. New York, John Wiley & Sons, Inc., 1951. Price, $6.50.

In this second edition, the author has kept the same form as the first edition, making extensive minor revisions. Several chapters have been rewritten, however, such as "The First Law of Thermodynamics," "The Second Law of Thermodynamics," "Available Energy," "The Flow of Gases and Vapors," and "General Thermodynamic Equations." With much new material added, the text presents a well-balanced treatment of engineering thermodynamics.

NOTES FROM THE BIOCHEMICAL RESEARCH FOUNDATION

ELLICE McDONALD, DIRECTOR

EFFECT OF 2-DESOXY-D-GLUCOSE ON RAT LIVER PHOSPHATASES AND PHOSPHATES

BY

M. H. ROSS AND J. G. ARCHER

2-Desoxy-D-glucose (2DG) was recently reported to competitively inhibit the anaerobic fermentation of glucose by yeast cells (1) and to inhibit cell division of fibroblasts in tissue culture (2). An investigation of the effects of 2DG on rat liver phosphatases and phosphates was initiated because dephosphorylation and phosphorylation are involved in the passage of sugars and phosphates through cell membranes (3, 4) and because glucose and phosphates enter the cell in a 1:1 ratio (4).

It has been found that 2DG, a structural analogue of glucose, has a different effect from that of glucose on phosphate metabolism.

MATERIALS AND METHODS

Adult male rats of the Wistar strain which had been allowed Fox Food Blox were divided into 4 groups of 10 rats each. A 0.3 gm./ml. 2DG solution (5) was injected intraperitoneally into 10 rats of one group. Each rat was given 1.5 grams/kilo of rat weight. Saline and glucose in the same volume and concentration were given to the same number of rats of two other groups. Ten more rats in a fourth group were given no injections. Food but not water was then withheld from all rats. Seven to eight hours later, the same rats were given 2DG, saline or glucose but in one-half the quantity used before. Twenty-four hours after beginning of injection and fasting, all rats were decapitated and permitted to bleed out. Small pieces of liver about 300 mg. were cut and weighed.

Extracts from each liver were prepared by grinding the piece of liver individually in a test tube with clean sand and extracting the mince with 5 ml. of distilled water for 30 minutes at 4° C. The ground liver mince was centrifuged and filtered through No. 2 Whatman filter paper.

Liver homogenates were prepared from another series of rats 16 of which were treated with glucose and 14 with 2DG. One piece of liver, approximately 2.5 gms., from each rat was weighed. Two pieces, one each from 2 rats which had received the same substance, were homogenized in 100 ml. of distilled water in a Waring Blendor for exactly 1 minute.

Alkaline phosphatase activity determinations were made on a 0.5 ml. portion of liver extract or of homogenate by introducing the preparation into 9.5 ml. of prewarmed (37° C.) barbital buffered substrate, pH 9.1. The final concentration of the substrate was 5 mg./ml. Blank determinations for inorganic phosphate content of the enzyme preparation or reagents and for the liberation of inorganic phosphate from tissue sources with water substituted for the glycerophosphate were made at the same time and under the same conditions. After incubation for exactly 1 hour, 2 ml. of a 50% trichloroacetic acid (TCA) solution were introduced into all enzyme-substrate and enzyme-blank mixtures and the solutions filtered. Inorganic phosphate was determined by the colorimetric method of King (6). Color was permitted to develop for 30 minutes and was measured with the Klett-Summerson photoelectric colorimeter equipped with a red filter No. 66.

Acid phosphatase activity determinations were made on 0.1 ml. portions of the same liver extracts used for the alkaline phosphatase determinations by introducing the preparation into 9.9 ml. of prewarmed (37° C.) acetate buffered substrate, pH 5.0. The final concentration of the substrate was 5 mg./ml. Blank determinations were made in the same way as for alkaline phosphatase.

The amount of inorganic phosphate liberated by the dephosphorylating enzymes from their natural substrates was determined. Ten rats were given glucose and fasted and ten rats were given 2DG and fasted. Two slices of liver, 4–5 mm. in thickness from each rat were immediately weighed and placed in 10 ml. of physiological saline, prewarmed to 37° C. These surviving liver slices were incubated for exactly 30 minutes. TCA was then added and these tissues homogenized in the Elvehjem-Potter homogenizer. Two other slices from each liver were immediately weighed, placed in 8% TCA solutions and homogenized. All homogenates were kept at room temperature for ½ hour, filtered and inorganic phosphate was determined.

RESULTS

Alkaline phosphatase activity was found to be higher in liver extracts and significantly higher in total liver homogenates from the 2DG treated rats than from the glucose treated rats (Table I). Acid phosphatase activity was not significantly changed in the liver extracts (Table I). The values for total nitrogen in whole liver or in the liver extracts from 2DG-treated, non-treated, saline-treated or glucose-treated rats were not found to be significantly different, therefore no correction was necessary in reporting alkaline and acid phosphatase activity.

TABLE I.—*Phosphate Liberated by Rat Liver Phosphatase Activity.*

Intraperitoneal Injection	Alkaline Phosphatase			Acid Phosphatase
	Extract γ P/mg. Mean ± S.E.$_{\text{mean}}$ n = 10	Daily Increased Activity in 2DG Treated Rats Mean	Homogenate γ P/mg. Mean ± S.E.$_{\text{mean}}$	Extract γ P/mg. Mean ± S.E.$_{\text{mean}}$ n = 10
None	0.46 ± 0.03	13.1%		11.78 ± 0.36
Saline	0.44 ± 0.04	26.6%		11.68 ± 0.38
Glucose	0.45 ± 0.25	20.9%	1.05 ± 0.089 (n = 8)	11.35 ± 0.59
2DG	0.52 ± 0.042		1.32 ± 0.100 (n = 7)	11.17 ± 0.72

Inorganic phosphate liberated by the total action of dephosphorylating enzymes on their natural substrates in surviving tissue slices was found to be significantly less in the livers from 2DG treated rats, 0.29 ± 0.0060γ P/mg. liver, than in the glucose treated rats, 0.31 ± 0.0073γ P/mg. liver.

TABLE II.—*Phosphate Content of Rat Livers and Blood.*

Intraperitoneal Injection	Inorganic	Total	Inorganic	Organic	Total
	γ P/mg. liver		γ P/100 ml. whole blood		
	Mean ± S.E.$_{\text{mean}}$ n = 10	Mean ± S.E.$_{\text{mean}}$ n = 10	Mean ± S.E.$_{\text{mean}}$ n = 10	Mean ± S.E.$_{\text{mean}}$ n = 10	Mean ± S.E.$_{\text{mean}}$ n = 10
Glucose	0.28 ± 0.012	4.01 ± 0.04	4.87 ± 0.15	48.47 ± 0.92	53.3 ± 0.90
2DG	0.22 ± 0.012	3.73 ± 0.05	5.21 ± 0.27	57.24 ± 1.36	62.4 ± 1.43

The inorganic and total phosphate present in the livers of rats treated with 2DG was very significantly decreased (Table II); the calculated organic phosphate present in liver was found to be decreased, 3.73γ P/mg. in glucose-treated rats and 3.52γ P/mg. in 2DG treated rats.

The organic and total phosphate content of whole blood from 2DG treated rats was found to be significantly increased (Table II) but the inorganic phosphate content was not significantly different.

DISCUSSION

Since there is a 1:1 ratio between phosphate uptake and assimilation of glucose (3, 4) any "blocking" which reduces the uptake of glucose into the cell will reduce the uptake and transport of phosphate across cell membranes. 2DG apparently restricts the amount of glucose that enters or is utilized by the cell (1, 2). This restriction may account for the reduced organic phosphate content of livers and the increased phosphate content of the blood of rats which have been treated with 2DG.

The increased activity of liver alkaline phosphatase which was found after 2DG treatment may be the result of a decreased rate of destruction of the enzyme or of an actual increase in amount of enzyme. It can not be the result of a blocking of phosphorylation; arsenate and dinitrophenol which are phosphorylation inhibitors (7) were given *in vivo* and did not alter the alkaline phosphatase activity of rat liver. Nor can it be due to direct activation of the enzyme; 2DG in concentrations as high as 0.1 M was added to the substrate-enzyme incubating mixture *in vitro* and did not alter the phosphatase activity.

The increased phosphatase activity found after 2DG treatment might be interpreted to indicate that there was greater utilization of substrate and therefore that there was a greater amount of inorganic phosphate present or liberated in the tissue. However, in surviving liver tissues there was less inorganic phosphate liberated by the action of dephosphorylating and phosphorylating enzymes on the naturally occurring substrates. This would suggest that one of the limiting factors *in vivo* in enzymatic hydrolysis of phosphoesters is not the amount of enzyme present, but the amount of the substrate available.

SUMMARY

The effect of 2-desoxy-D-glucose, an analogue of glucose, was compared with the effect of glucose on phosphate metabolism in rats. It was found that the amounts of both the inorganic and the organic phosphates were reduced in the liver but the amount of organic phosphates was increased in the whole blood. The amount of inorganic phosphate liberated by dephosphorylating enzymes in surviving liver slices was found to be reduced even though the alkaline phosphatase activity was found to be increased.

These findings suggest that 2DG reduces the amount of phosphate which enters the liver cell and therefore the amount of phosphoester substrates available for dephosphorylation.

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CURRENT TOPICS

A New High-Speed Cathode-Ray Tube.—At the I. R. E. Convention, a new type of cathode-ray tube which allows the observation of heretofore unseen electrical and nuclear events which occur in one ten billionth of a second was revealed by H. J. Peake and R. W. Rochelle of the Naval Research Laboratory, Washington, D. C. The tube operates much like a television picture tube except that the electron beam, in tracing patterns on the tube face, moves at speeds as high as 70,000 miles per hour, or over one-third the speed of light. The tube opens the door to study in such fields as nuclear fission processes, the generation of radar signals, and electrical voltage breakdown of materials.

New Portable Field Telephone.—A new and improved portable field telephone set has been developed by Bell Telephone Laboratories to meet the forward-looking program of the Signal Corps.

The new set embodies all the new technical knowledge and telephone experience acquired in the last 15 years. Basically it has been modeled to a considerable extent after the new Bell System 500-set which has recently gone into production. Designed to meet the performance requirements of the Signal Corps Engineering Laboratories the field set has been markedly altered for military use and incorporates a number of special military features.

The new set is lighter in weight, about eight pounds compared to the eleven pounds of the present set, thanks to lighter weight components and the use of light weight magnesium in the container. It is smaller, too, about the size of a loaf of bread. It is rugged; tough new plastics are used for the handset, and the entire set is expected to survive parachute drops with ease. It is very flexible; different circuit arrangements are available with the flick of a switch—common battery, local battery, or a combination of these. In an emergency the set operates efficiently for several miles without batteries—on voice power alone. The handset is shaved at the ear-piece end so it can fit beneath a battle helmet with comfort. The mouthpiece, or transmitter, stands up nicely to nearby gun blast. It works effectively at 40 degrees below zero or in the heat of 130 degrees, and at altitudes over 10,000 feet. It can be dunked in water without effect; the entire set is waterproofed by a series of gasket seals. It can be operated by a soldier wearing long, heavy Artic mitts.

The signal "bell"—actually a sharp tapping sound such as a woodpecker makes—can be adjusted in loudness from complete silence, through a whisper, to a loud penetrating alarm.

Like the telephone set in your home or office, the new set is a basic unit of the military communications network. The new military set can be connected by wires directly to another set, to a switchboard or, with the flick of a switch, to a remote transmitter for radio communication.

An unusual problem in the design of the set was posed by two military requirements; first, that the set be entirely waterproof and, secondly, that it be transportable at altitudes as high as 50,000 feet. The first could be easily met by completely sealing the set with gaskets; but then, at 50,000 feet, there would be normal air pressure inside the set but very little air pressure on the outside—an imbalance that might cause serious mechanical distortion or even breakage. Bell Laboratories engineers solved the difficulty by inserting tiny ceramic valves in the set and in the handle of the handset. The ceramic—about the size of the head of a carpet tack—allows air to pass through so that air pressures inside and outside the set are the same at any altitude—and yet it keeps water out.

"Robot Brain" to Probe Secrets of Oil.—The Atlantic Refining Company has announced the development of a "robot brain" which will analyze petroleum products in one-tenth the time required by existing methods. This modern analytical tool will analyze a mere trace of gas or liquid, and in a matter of minutes record the complete chemical composition on a typed sheet of paper.

This was achieved by the linking together of an electronic counter and a mass spectrometer, one of the most important analytical instruments of the petroleum industry. The computer, dubbed the "Miniac," was developed for Atlantic by Physical Research Laboratories of Pasadena, California.

"The union of these two complex electronic instruments," according to Dr. Young, of Atlantic's Philadelphia research staff, "promises more than a ten-fold speed-up in obtaining vital information in the continual search for better quality gasolines and lubricants."

According to George Green of Physical Research Laboratories, designer of Miniac, this instrument can also be used separately on many other problems requiring high speed complex calculations. So applied, it can compute at the rate of 100,000 digits per second, or over 10,000 times as fast as the fastest human with pencil and paper.

An important link in the combination of Miniac with the mass spectrometer was a "selector" designed for Atlantic by Consolidated Engineering Corporation of Pasadena.

After almost two years of development, Miniac is nearly ready to be put in operation in Atlantic's Research Laboratories and will shortly undergo final tests. The company plans to make this important development available for industry-wide usage.

"Vibro Pump."—The invention of a revolutionary new type pump for various industrial and aviation uses was disclosed recently by the Drexel Institute of Technology. The pump, expecially suited for use in the chemical, oil and food industries, was developed in Drexel's laboratories by William Gemeinhardt, a former flier and research engineer in the Hungarian Air Force.

The principle of the new pump is vibration instead of rotation. It has but one vane. A curved axle rotates within a hermetically sealed flexible tube which extends into the pump chamber. Due to its curvature, the axle moves the flexible tubing in a circular arc. The vane, attached to the end of the tube travels the same path and pushes liquid out through the exit hole of the pump chamber.

In explaining his invention, to which Gemeinhardt has given the name of "Vibro Pump," the inventor said: "It has no packing whatever, and therefore, requires no lubrication. Packing must be lubricated, and this creates contamination. The Vibro Pump is so simple it can be taken apart and cleaned in a matter of minutes. It has no valves and no bearings. It has only two main parts, the housing and the agitator." Since the "Vibro Pump" is hermetically sealed, there is no possiblity of leakage or escape of fumes during the process of pumping explosive or inflammable fluids, such as gasoline or alcohol; when used for chemical purposes, there is no contamination of liquids. Since it contains no sliding or rubbing parts, the pump can handle crystals, sand, or dirt in liquids. It can be run by every type of motor.

Hand Pyrometer with Two Scale Ranges.—A new hand pyrometer with two scale ranges for the rapid and convenient measurement of surface, liquid, gas, and molten metal temperatures has been announced by the General Electric Meter and Instrument Department.

Designated as the Type FH-1, the new pyrometer is especially useful where a temperature detector does not need to be installed permanently. Its two scale ranges are 0-500 F and 0-1500 F, and the change from one scale to the other is accomplished by the flick of a switch.

Three interchangeable tips available for the new pyrometer include a surface tip, an immersion tip for liquids and molten metals, and a two-prong contact tip. These tips, together with flexible and rigid extension arms, can be easily changed.

The automatic cold-junction compensation feature of the FH-1 eliminates the need for manual adjustment of the pointer for variations in temperature of the instrument or its surrounding atmosphere. Readings can be made directly from either scale of the instrument since no calculations or corrections are needed.

Typical applications include temperature checks of plastic molds, ovens, alloys with low melting points, and pre-heated metals for welding.

Another high altitude rocket will be launched by the Navy this spring in an attempt to beat the record of 135 miles made by the Viking No. 7 last August. Rocket No. 8 will be a redesigned Martin Viking with greater fuel capacity, power plant generating approximately 20,000 pounds of thrust. Telemetering equipment will be carried, as before, to furnish readings on altitude, speed, temperature, and cosmic ray count.

A general purpose master control panel built at the Naval Ordnance Laboratory, White Oaks, Md., converts a regular IBM Card-Programmed Calculator into the equivalent of a room-sized electronic brain. The 24 × 28 inch panel makes possible such operations as automatic generation of elementary trigonometric, hyperbolic and exponential functions and their inverses to seven decimal points in one second, and the printing, storing, punching, or retention within the computer of answers.

High Thermal Conductivity Ceramics.—Rutgers University has developed beryllia type ceramics which have very high thermal conductivities, the best of which has a conductivity of 90 (Btu./hr.)(sq. ft.)//(deg. F/ft.) at 140°F. This is nearly as good as aluminum which has a conductivity of 118 and is at least 16 times better than classical ceramics which have a conductivity ranging fron 0 to 5 (Btu./hr.) (sq. ft.)//(deg. F.) These types of ceramics can be prepared by normal ceramic processes of fabrication including pressing, extrusion, and casting. Adequate precautions must be taken in the use of beryllia from a toxicity standpoint, however. Further work is being carried out on a large number of new ceramic systems containing oxides of cerium, lanthanum, vanadium, and neodymium.

Axostat.—A new electronic instrument, called the Axostat, which will assist physicians in detecting and diagnosing heart ailments was described during the Medical Electronics session of the annual meeting of the Institute of Radio Engineers. Augmenting, but not replacing the conventional electrocardiograph, the "Axostat" gives diagnosticians another "view" of the operation of the heart which may reveal abnormal heart conditions not readily detectable by conventional means. Design and operation of the Axostat, which supplies a graphic tracing of the minute electrical currents produced by the contractions of the heart muscles, was described in a paper by the device's developers, B. P. McKay, W. E. Romans, D. A. Brody and R. C. Little, members of the staff of the University of Tennessee Medical Units.

Resistors.—The International Resistance Company, of Philadelphia, announces two new resistors, designed to be produced on the nation's first mechanized assembly line for Deposited Carbon (Type DCC) and Boron Carbon (Type BOC) resistors. Physically alike except in color, both types provide higher resistance values in less space and at a lower cost than wire wound precisions. As an added factor, the Boron Carbon resistor provides a greater degree of temperature stability. Both units are conservatively rated at $\frac{1}{2}$ watt. Body length is $\frac{9}{16}$ in.; diameter of outside caps is $\frac{5}{32}$ in. The applications include precise military electronic equipment, radar, gun directors, instruments, and meter multipliers.

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Radioactivity of Archeological Specimens.—High in the stratosphere is going on a chemical process which has resulted in an accumulation on the earth of about 80 tons of radioactive carbons. Dr. Willard Frank Libby, a University of Chicago scientist, received the 1951 Research Corporation Award recently for developing a method and apparatus to measure the residual carbon radioactivity in archeological specimens and thus determine their ages with an accuracy hitherto unknown. His contribution has been termed one of the most important advances of the century to archeological progress.

Dr. Libby said in accepting the award that his method of dating is based on the known inventory of 80 tons of radioactive carbon atoms in the world.

His studies so far have set the Ice Age at 10,000 years ago instead of 25,000 years, dated the world's oldest village, confirmed the date of one of the oldest known Biblical manuscripts, and contributed vital dates to the history of the first men in America.

The radiocarbon is produced in a series of natural atom-smashing events at their most active about eight miles above the earth's surface. Carrying an energy wallop thousands of times greater than produced by man-made atom smashers, cosmic rays enter the atmosphere from outer space to shatter the nuclei of atoms of atmospheric gases. Other reactions take place subsequently to result in carbon dioxide absorbed by plants and, in turn, eaten by animals.

At death of the animal or vegetable matter, the radioactive carbon content is no longer replenished by food intake and the activity of the residual radiocarbons can be measured by Dr. Libby's special apparatus involving the principle of Geiger counters to determine how long before that the specimens were alive.

Charactron Hi-Speed Printer.—A unique development combining electronics and dry photographic techniques for the first time to provide high-speed, automatic recording of intelligence at rates as high as 10,000 characters per second was described recently by J. T. McNaney, inventor of the Charactron, a special-purpose cathode-ray tube.

McNaney, a senior electronics engineer for Consolidated Vultee Aircraft Corporation (Convair), San Diego, Calif., told members of the Institute of Radio Engineers that the Charactron tube "would be of immense value in many applications requiring high-speed visual presentation of information on a direct-viewing screen or reproduced for a permanent record on ordinary newsprint or other low-cost media."

"This reproducing equipment, referred to as a Charactron Hi-Speed Printer, utilizes the Charactron tube to produce a printing speed of approximately 20 inches of paper per second and will satisfy the need for voluminous recording at high speeds," McNaney said.

"We believe that the Xerography process, developed by the Haloid Company of Rochester, N. Y., will be ideally suited for use in connection with the Charactron tube as a means of recording the output. Convair has had discussions with the Haloid Company with a view to a cooperative development of this equipment.

"This printing would be done directly and continuously on newsprint, multilith, or any other desired recording medium without film or costly and cumbersome chemical processing."

Among the more general applications of the Charactron tube are the data conversion and tabulation of analog or digital information, high-speed communications, for monitoring and message display equipment, and for computer read-out.

Current development work includes application of the Charactron to the computer field and to special military projects.

One important type of data converter that McNaney referred to is equipment that will measure physical quantities in the form of electrical potentials and present them as three-place numerals on the viewing screen of the Charactron tube.

McNaney said the Charactron incorporates a design unique among cathode-ray tubes. A matrix containing character-shaped openings is located between an electron gun and the fluorescent screen at the viewing end of the tube. A stream of electrons selectively directed through the matrix openings produces a shaped beam that provides a presentation of characters on the screen of the tube, where they can be read or recorded. An electro-static deflection system is utilized for the character selection of the matrix, and either electro-static or electro-magnetic deflection—similar to that used with television tubes—is used for placing the character images on the viewing screen. In this manner, the proper sequence of applied deflection voltages selects and positions the matrix characters so that message signals are translated into visual intelligence.

A new gas proof uniform developed by the Chemical Corps Research and Engineering Command is designed to protect its wearer against both chemical and biological agents, yet is comfortable enough to permit carrying on normal duties. The complete outfit includes one-piece impermeable suit, a three-piece cooling suit and protective gloves and boot covers. The impermeable suit is of non-inflammable butyl rubber. The cooling suit consists of trousers, jacket and hood, all of diaper cloth, which are worn over the impermeable suit, drenched with water. All items of the outfit are easily decontaminated.

Smaller, Lighter, More Versatile FHP Motors.—A new line of fractional horsepower motors embodying an entirely new concept of motor design and manufacture has been announced by the General Electric Company's Fractional Horsepower Motor Department.

Designated as "Form G," the new motors are the result of nearly a decade of developmental engineering and research, and incorporate many radically different and advanced design features.

According to G-E engineers who worked on the project, the Form G motor weighs as much as 51 per cent less per horsepower than the models it replaces and is considerably smaller in size. At the same time, its versatility of application has been broadened and its appearance modernized.

The motors are available in open dripproof and totally enclosed fan-cooled models in Types K (polyphase), KC (capacitor start), KH (split phase), and KCP (permanent split capacitor). These have hundreds of applications—on pumps, fans, blowers, compressors, office and home appliances, motorized tools of all sorts, etc. The design principles ultimately will be adapted to motors for more specialized uses as the Form G line expands, the engineers said.

The advanced design incorporates a completely new insulation system developed by G.E. especially for this project It consists of a special nylon material scientifically combined with Formex* wire and Glyptal* varnish to give the motors longer life.

The Form G also makes more efficient use of existing materials, and features a long list of design "firsts." Among these are new bearings, lubrication system, insulation, ventilation, mountings, windings, end shields, terminal board, and leads.

In addition, the new motors are engineered for dissipation of heat losses while retaining outstanding performance characteristics in comparison to their small size.

Being smaller and lighter, the Form G permits installation of maximum power in minimum space. Its use also decreases transportation and storage costs on motors and motorized devices, makes handling easier in factories and warehouses, and eliminates the need for heavy mounts on machines.

Open dripproof models are as much as 48 per cent lighter than previous motors of equivalent rating, while the totally enclosed fan-cooled types weigh less than half as much in some cases.

With the improved bearings, lubrication, and insulation, the Form G general purpose sleeve-bearing motor offers a wider range of application, and will eliminate, in many instances, the extra expense of special enclosures or ball bearings. It is the only motor of its type recommended for all-angle operation.

Although everything about the Form G has been pared down to the essential, functional, fundamental, it conforms fully to all NEMA specifications. The motors will be offered in a complete range of standard horsepowers, speeds, voltages, and frequencies.

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* Reg. Trade-Marks of the General Electric Co.